

HEAT TREATMENT
OF
METALS

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by

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Principles and Practice of Heat Treatment

CHAPTER I

General Principles

IT is a noteworthy fact that the trend of modern engineering design is generally towards greater strength allied to lighter weight in the various materials used for constructional purposes. In the field of engineering metals this demand, often urgent, has led to the development of many new alloys to meet the changed ideas of present-day designers. Factors of safety which in the past would have been considered by competent engineers to be quite normal, are now regarded as extravagantly high. In order to offset any possible danger which may arise from this reduction in weight and dimensions, modern metals must necessarily be reliable as well as strong, and it is characteristic of present metallurgical practice in preparing the engineer's raw materials that scientific control is widely adopted. This quality of reliability is partly conferred by the high purity of the alloys, reflecting the care with which the material has been manufactured, and partly by exact and well-controlled heat treatment. The latter factor is of prime importance in factories engaged in mass production, since the physical properties of each part must conform, within narrow limits, to a definite specification. While it is true that reputable manufacturers of raw materials work to very high standards and, indeed, often take pride in bettering existing standards, much of their efforts are nullified by erratic and careless heat treatment in subsequent manufacturing operations.

The aircraft and automobile branches of engineering are two outstanding examples of industries where the truth of these

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General Principles

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The aircraft and automobile branches of engineering are two outstanding examples of industries where the truth of these

statements are widely recognised. In aircraft especially, weight is of necessity cut down to the absolute minimum and all heat-treated components must be dependable to the limit of their physical properties. The same is true, perhaps to a lesser extent, in the automobile industry and in many other branches of engineering where efficiency and economy are secured by the adoption of special steels or non-ferrous alloys

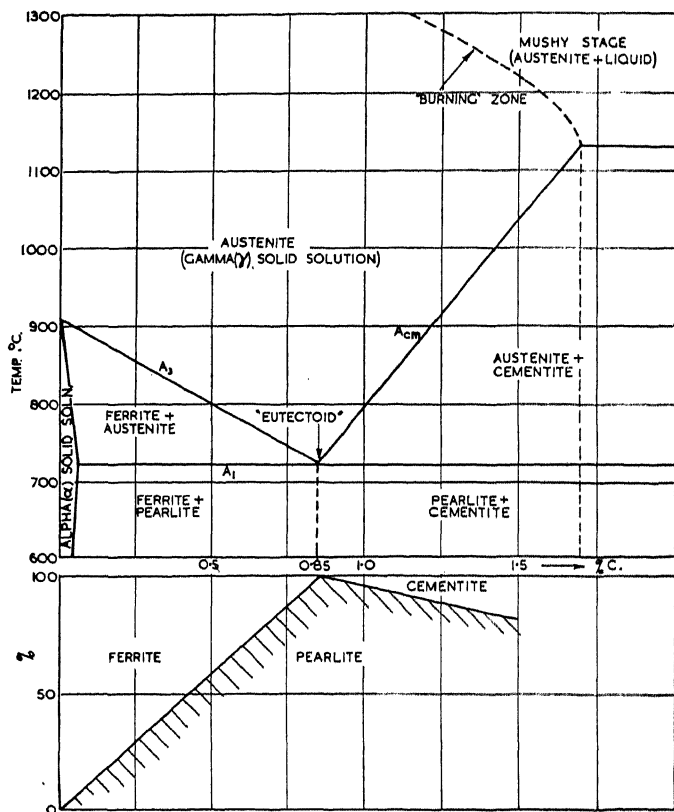


Fig. 1.—A graphical representation of the changes which take place in carbon steel when it is heated

in construction. In order to obtain reproducible results with these materials, it is essential that the heat treatment should be uniform and under complete control, and that all variable factors should, so far as possible, be eliminated. This high

standard can only be achieved by well-designed furnace equipment and intelligent appreciation of all the factors involved.

The scope of heat treatment covers a very wide field indeed. It is well known that steels can be subjected to forms of treatment by which their characteristics are profoundly altered, and similarly there is a large and steadily increasing number of other alloys which can be influenced in the same way. Not all alloys, however, will respond in the desired manner, the ability to do so being bound up in their inner constitution. The ability of metals to form compounds with each other, solid solutions and even allotropy of one or more components of the alloy, play a large part in determining the final physical properties of the combination.

Principles for the Heat Treatment of Steel

Among the "heat-treatable" alloys, the alloys of iron are, of course, the largest class, and are by far the most important economically. Apart from cast irons, some of which can be heat-treated, the majority of the steels respond in greater or less degree to the influence of heat.

The so-called plain carbon steels are binary alloys of iron and carbon, in theory at least, although commercial carbon steels always contain minor percentages of impurities and, invariably, appreciable amounts of manganese. The alloy steels of commerce are more complex alloys of iron and carbon which contain in addition various percentages of other metals such as nickel, chromium, tungsten and molybdenum, each of which is added with a view to improving the hardness, strength, ductility or other physical properties of the steel. The basis of the heat treatment of the complex alloys, however, is to be found in the carbon steels, and for this reason much research has been devoted to following the changes which occur when these steels are heated. Early workers in this field demonstrated that pure iron and steel showed well marked critical points at definite temperatures both on heating and cooling, each of these points marking a well-defined physical change. For example, if pure iron is heated slowly and regularly and the temperature observed with a sensitive thermocouple, a distinct halt in the heating ("arrest") is observed at 910°C . This halt marks a physical change in the constitution of the iron and signals the transformation of pure iron from the crystalline form stable at ordinary temperatures to that form

stable only above the so-called critical temperature. The halt observed on heating is caused by an absorption of heat during this rearrangement of molecules within the crystals. The reverse phenomenon occurs at approximately the same temperature on cooling, a halt being observed again due to an evolution of heat accompanied by a crystalline change in the metal. It is thus clear that pure iron can exist in two allotropic forms: (a) a low temperature form stable up to 910°C ., and (b) a form stable above 910°C .

These facts, as well as the influence of carbon on the occurrence of these and other critical points are shown graphically



Darwins Limited

Fig. 2.—Forged medium carbon steel showing ferrite (light areas) and pearlite (dark areas). The dark areas alone contain approximately 0.85 carbon (eutectoid composition) the excess of iron crystallising out separately, thus making the average carbon content 0.4%

in Fig. 1, but before going on to consider this important phase of the subject, it might be well to enumerate the various properties of the two kinds of iron mentioned above. The form which is stable at ordinary temperatures is designated "alpha" iron to distinguish it from the high temperature modification, "gamma." Some of the diverse properties of these two forms of the same element are tabulated below:

"Alpha" iron—

Magnetic (up to 770° C.).

Relatively good electrical conductor.

Carbides almost completely insoluble (does not readily form solid solutions).

"Gamma" iron—

Completely non-magnetic.

Poor Conductor.

Carbides completely soluble (forms solid solutions readily).

Influence of Carbon on the Critical Points

When carbon is alloyed with iron it combines with some of the iron to form the chemical compound Fe_3C , or iron carbide, an extremely hard, brittle material. While this carbide is quite soluble in gamma iron, as was shown in the table above, it is almost completely insoluble in alpha, under conditions of true equilibrium. It may seem a strange idea to speak of "solubility" in solid alloys, but solution and precipitation occur frequently at temperatures far below the melting range of a great number of ferrous and non-ferrous alloys, in a manner perfectly analogous to the familiar phenomenon observed with many liquids. As is shown in Fig. 1, increase in the amount of carbide, or what amounts to the same thing, increase in the percentage of carbon in the alloy progressively lowers the temperature of this critical point until a minimum is reached at about 0.85% carbon. As the carbon increases up to this amount (known as the "eutectoid composition") a new critical point appears at 723° C. and marks the beginning of the transformation which results in the ultimate formation of the homogeneous solid solution "austenite." The carbon in any normal alloy always forms the peculiar iron-iron carbide mixture to the extent of 0.85% carbon, and this eutectoid mixture has the constant transformation temperature of 723° C., which is conventionally known as the " A_1 " point. The upper point which marks the end of the transformation is similarly known as the

"A," point, and shows that the final transformation into the homogeneous solid solution is complete. When the carbon content is greater than the eutectoid ratio, free carbide is present in the alloy, and while, in this case, the pearlite or eutectoid mixture transforms into austenite at 723° C., the free carbide, or cementite, does not go into solution until the higher temperature shown by the line " A_{cm} " is reached. The lower portion of the diagram represents the relative proportions of alpha iron, or ferrite, pearlite and cementite, in the range of alloys shown, when normally cooled (see Fig. 2).

Because of the fact that these critical points do not always occur at exactly the same temperature on heating as on cooling, they are further referred to as " A_c " on heating and " A_r " on cooling. It usually happens that the " A_c " temperatures occur somewhat higher than the " A_r " which correspond.

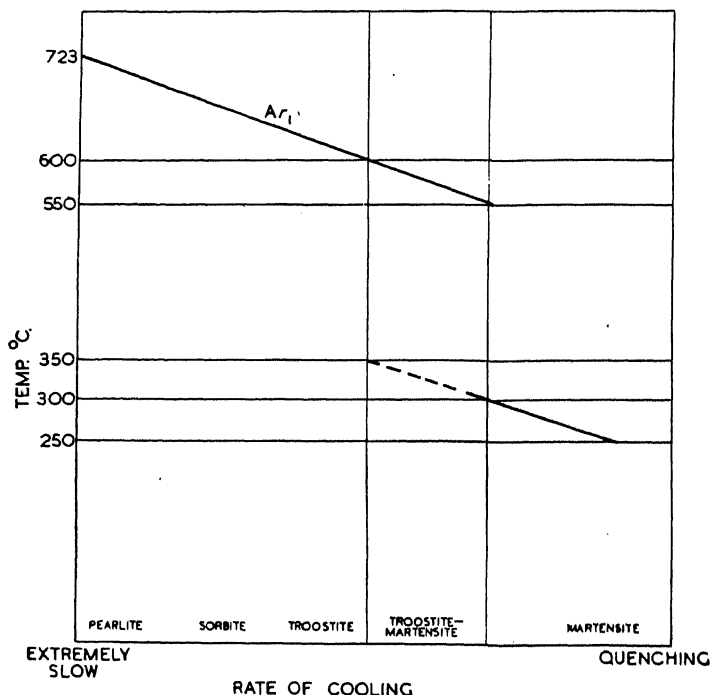


Fig. 3.—Showing the influence of rate of cooling on the occurrence of A_{r1}

Summing up, then, two points of great practical importance emerge. Firstly, for each particular alloy, there is a definite temperature above which a homogeneous solid solution is formed, and secondly, when this solid solution is formed, recrystallisation or obliteration of previous structure simultaneously occurs. The practical implications of these changes will now be discussed.

The Mechanism of Annealing, Hardening and Tempering

It is not the present writer's intention to enter into a lengthy discussion on the various current theories of the exact nature of hardening steel. It will be sufficient to state here that, in general, the hardness of steel depends on it being first of all heated to some temperature above A_{c_1} , thus forming a solid solution, the rate at which this solid solution is cooled, and the "hardenability" of the steel itself. Steel containing less than about 0.35% carbon, in the absence of other alloys, will be difficult to harden even by rapid quenching, while, on the other hand, a high carbon steel may be readily hardened by a comparatively mild quench in oil. This property is somewhat loosely termed "hardenability," and in this case is a direct function of the carbon content. The temperature at which the transformation occurs on cooling has also a profound influence on the hardness. As the rate of cooling increases, this temperature (A_{r_1}) drops from the normal 723° in a regular manner until a temperature of 600° is reached when, with faster rates of cooling, the transformation splits, and finally, as cooling rates still faster are attained, suddenly drops and occurs at temperatures in the neighbourhood of 300° C. The various cooling rates correspond to definite microstructures. With increasing cooling rates, the normal pearlite is modified first to sorbite ("emulsified pearlite"), then troostite, with gradual increase in hardness. The sudden drop in A_{r_1} to 300° C. is marked by the appearance of martensite, a constituent which always appears in fully hardened steel and is thought to be a "forced" solution of Fe_3C in alpha iron. All these constituents can be readily identified by means of the microscope, and the various changes are shown graphically on Fig. 3. It will thus be appreciated that the heat-treater has a very wide control of the final condition of any steel by merely varying the rate of cooling from above A_{r_1} , so that very slow cooling, such as

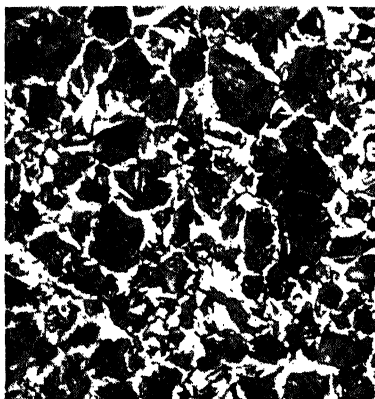
cooling with the furnace, might produce a soft, ductile pearlitic steel, while rapid cooling, as produced by water quenching, will make the steel glass hard and comparatively brittle (Fig. 4 (a) and (b)). Full annealing, then, is carried out by heating the steel to some temperature about 50° C. higher than A_{c3} , holding at that temperature sufficiently long to allow the heat to equalise throughout the mass, and cooling, either in the furnace or in lime, ashes, etc. The necessary point to observe is that no matter how conducted, the rate of cooling must be exceedingly slow, especially when passing through the critical range. Normalising consists of heating as for annealing, but removing from the furnace and cooling the part in still air, which, as would be expected, gives a somewhat harder product. The various forms of quenching, as in oil or water, give hardnesses up to the maximum obtainable. Oil is always much milder in effect than cold water, but this can be largely offset by increasing carbon content in the steel or, as will be seen later, by other alloying elements in the steel. For example, a commercial 0.4% carbon steel would require a cold water quench to produce the full hardness, while a 1.25% carbon razor steel would probably be much harder even with an oil quench.

The tempering of steel is an art which calls for some degree of skill if best results are to be obtained, and more will be said on the practical side later. When steel is fully hardened it is in a very unstable condition and, especially if it has been water quenched, in a state of some considerable strain. In tempering, the quenched parts are re-heated to a moderate temperature with two objects in view:

- (a) to remove, or at least relieve the strain;
- ✓(b) to modify the unstable martensite to a more stable condition.

As the tempering temperature is increased, the martensite is resolved in turn into slightly softer constituents until, finally, just short of A_{c1} , it is again pearlitic. Thus a given hardness can be imparted to a steel by controlled quenching, that is directly; or indirectly, by fully hardening and tempering back to a suitable temperature. This latter method is usually adopted since it serves to relieve internal strains as well as to stabilise or transform the martensite (Fig. 5).

Another factor of great importance in hardening is grain growth. This depends on the time and temperature at which



0.38% carbon steel, normalised 850° C. Pearlite with ferrite network. $\times 250$

(a)



0.38% carbon steel, water-quenched 850° C. Well-marked acicular martensite. $\times 250$

(b)

Fig. 4

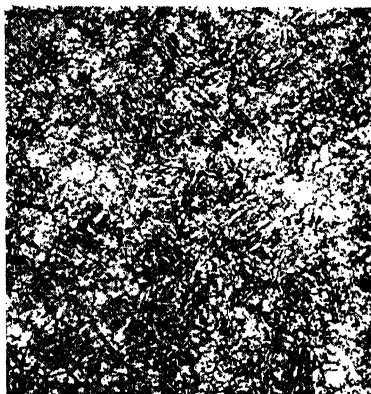


Fig. 5.—0.38% carbon steel, water-quenched 850° C. Tempered 600° C., dense sorbite structure. $\times 250$

the piece is held before cooling. While re-crystallisation takes place above the A_c temperature, the amount above this temperature the piece is taken and the time it is held above this temperature both influence the final grain size. Prolonged

heating at high temperatures leads to large grains and poor ductility, the fracture of such steels being coarse and "open" and the material generally brittle. Steel in this condition can be refined by reheating to a temperature just over A_c , and air cooling, thus producing a great improvement in ductility. The quality of the steel also affects the grain size produced by any given treatment, some steels being inherently fine grain, or having the property of resisting grain growth to some extent, while others are inherently coarse grained, forming large crystals readily. The inherent grain size of any steel is largely determined by the manufacturing methods adopted in the melting shop, and is largely under the control of the steelmaker.

Influence of Alloys

When alloying elements are added to plain carbon steels, the aim is usually to modify some physical property such as strength, ductility or "hardenability" in some way. Nickel, for example, enters into solid solution with the ferrite and strengthens it, at the same time definitely lowering both the A_r and A_c temperatures. In effect it behaves very similarly to carbon, since nickel steels in general require lower hardening temperatures than the corresponding carbon steels. Manganese also lowers the A_1 point but at the same time it forms a carbide with the carbon, along with the iron. Chromium, tungsten and molybdenum, on the other hand, raise the A_r and A_c ranges and also readily form carbides which generally require a high temperature to take them into solid solution. Such steels are characterised by unusually high hardening temperatures. An outstanding example of this type of steel is given by high-speed tool steel which requires a hardening temperature of some 1300°C . for absorption of free carbide.

Alloy steels usually do not require such rapid rates of cooling to place them in the fully hardened condition, oil quenching and sometimes simple air cooling being sufficient. The usual engineering grades of nickel and nickel-chromium steels, for example, are oil hardening and, in the higher carbon tool grades, even air hardening. The effect of the lower cooling velocities necessary with alloy steels is that less internal strain is set up in the material on hardening and there is less risk of cracking and distortion, especially in tools, etc., of intricate shape. The great advantage of alloy steels over their carbon

counterparts is that higher physical strength is obtained in addition to an often simpler heat treatment.

Practical Data

Carbon tool steels range usually from about 0.7% carbon to 1.5% carbon. Recommended hardening temperatures for commercial grades from 1.0% upwards are in the neighbourhood of 760° C. to 780° C. Below this carbon content down to about 0.7%, temperatures rise from 780° C. to 820° C. Low hardening temperatures are adopted over the eutectoid and higher carbon range since these steels are very easily burned if taken near the "mushy" range shown in Fig. 1.

The usual range of nickel steels containing 1%, 3% and 5% with varying percentages of carbon are refined and hardened at temperatures in the neighbourhood of 800° to 860° C. The nickel-chrome group covers many different compositions from rustless steel to girders and gearwheels, while the straight chrome steels also form a large class, covering stainless and heat-resisting types, ball bearings and tools. In addition, other elements are often added with a view to modifying some property such as temper brittleness, for which purpose molybdenum is often added as a counteracting agent to nickel-chrome steels.

The tungsten group of tool steels covering fast-finishing and high-speed types are hardened from an extremely high temperature, most of this group being tungsten-chrome-vanadium alloys or similar steels.

This wide variety may at first be rather confusing, although the outline above does not by any means cover all the alloy types which have been developed. Fortunately, however, the manufacturers are always willing to supply the necessary data for their own particular products. At the same time, if the composition of a particular steel is known, it is always possible to ascertain the best treatment experimentally. More particular details of various types of steel will be given later under their appropriate sections.

CHAPTER II

Furnaces and Equipment

In the previous chapter some theoretical explanation was given of the way in which steel could be influenced by heat. There now remains to consider how these principles are applied on a commercial scale.

At first sight it would seem to be a comparatively simple matter to heat a piece of steel to the correct temperature, merely demanding a furnace of some sort for this to be done. It should be borne in mind, however, that not all furnaces are equally efficient for the purpose. Some are likely to be both costly and inefficient. The design of a furnace for any particular duty calls for a good deal of experience, and before any choice can be made the following are some of the factors which will have to be taken into consideration :

- (a) Cost of fuel (or electric power).
- (b) Ease in maintaining uniform temperature in the furnace load.
- (c) Ease of control of temperature.
- (d) Chemical nature of the furnace atmosphere and its influence on the work.
- (e) Labour required to work the furnace.
- (f) Nature of the operations themselves (continuous or intermittent).
- (g) Relative costs of repairs and general maintenance.

Comparatively simple furnaces of the reverberatory type using solid fuel find their widest application in the treatment (such as normalising) of heavy material. While the fuel cost is low, there is little or no control over the temperature and the furnace atmosphere is also very variable. Such a furnace requires a good chimney and consequently the first cost of the plant is rather high. Repairs and maintenance charges are also on the high side. Such furnaces depend entirely on the

skill of the furnaceman to produce good results and are quite unfitted for really accurate treatment.

Modern plants which have been laid down for large-scale heat treatment use either gas or electric heating. In the "heavy" industries, reheating furnaces for forging or rolling are almost universally fired with producer gas. Such furnaces are usually manually controlled, although pyrometer gear is often fitted, and they can be built large enough to take the largest ingots or forgings made. These furnaces are also utilised for heat-treating heavy forgings and plates with considerable

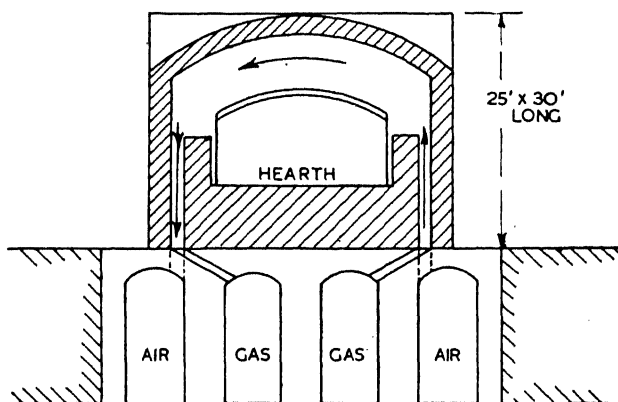


Fig. 6.—Cross-section of large furnace used for heat-treating forgings and other large work

success. They are costly to build and maintain but fuel costs are very low. Producer gas itself is a poor fuel, having a low calorific value, and in order to obtain the temperatures necessary, the air for combustion is first superheated by passing it through regenerators. These regenerators are heated by the waste gases from the furnace. In some cases the gas is also regenerated in this manner. Fig. 6 shows diagrammatically a cross-section of such a furnace of the type used for heating large forgings. It will be seen that the gas and air enters from one side, passes round the roof, and leaves by the other. The chambers below house honeycombs of firebrick which serve as regenerators, the pair on the exhaust side being heated by the burnt gases. After about half an hour the direction of the gas and air is reversed, so that one pair of regenerators

are heated while the other pair give up their heat to the cold gas and air. This half-hourly reversal is accomplished by means of valves and ensures an even distribution of heat over the furnace as well as making the attainment of high temperatures possible. Naturally, the heat storage of a large furnace of this type is considerable, and all the advantages of cheap fuel might be lost if it is only worked intermittently. Consequently the chief application of these furnaces is for work of a continuous nature. Their chief disadvantage is that no bottom heat can be obtained, the hearth always tending to be cooler than the crown. If uniform heating is of prime importance,—as it is in most heat treatment—the work must be supported clear of the hearth, and some attempt made to divert the gases

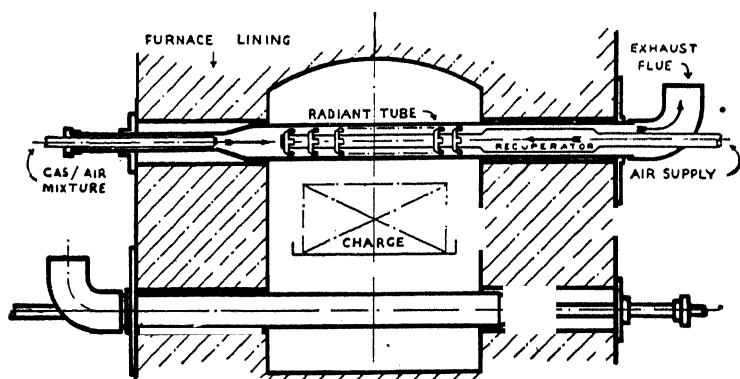


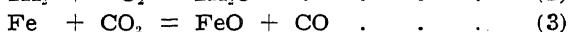
Fig. 7.—Recuperative radiant tube furnace installation

Birmingham Electric Furnaces Ltd.

below the work as well as above it. The only temperature control possible with these furnaces is by regulating the supply of gas and air. This has to be done by hand, since the gas is of variable composition and does not lend itself readily to automatic control. Despite these disadvantages, this is by far the cheapest means of heating large masses of steel either for forging or quenching, and is efficient for this purpose.

The atmosphere of gas furnaces, in which the gas burns in the chamber holding the work, is susceptible to a certain amount of control. If the gas is burned with an excess of air there will be free oxygen in the furnace atmosphere, and the condition known to furnacemen as a "sharp heat" will be obtained. In this atmosphere steel is readily oxidised, while

the surface may even be decarburised. This may not be of much consequence when dealing with large masses, but smaller pieces may be excessively scaled in such an atmosphere. The usual practice in attempting to avoid this is to maintain a so-called "hazy" heat, that is, to have a slight excess of gas in the flame, and by suitable manipulation of the chimney dampers to maintain a low gas velocity through the furnace. This provides a slight outward pressure in the furnace chamber, thus preventing ingress of cold air at doors or other openings. When gas is completely burned, nearly all the products of combustion have some action on the steel being heated. Incomplete combustion helps to minimise this effect by producing an atmosphere which is less active chemically. The combustible elements in either producer gas or coal gas are carbon compounds or hydrogen. The following equations show the effect of complete combustion on iron.



If excess air is present, of course,



If there is a deficiency of air in the furnace, however, carbon monoxide (CO) replaces the dioxide (CO₂), with the result that the bulk of the oxidation or scaling arises from the presence of water vapour in the atmosphere as shown in equation (4) above. This minimises scaling, as well as decarburisation, but, as will be seen later, it is now possible to control the atmosphere of certain types of furnaces so as to eliminate scale entirely.

In the majority of hardening shops, however, heat treatment is confined to relatively small parts. Most shops have to deal with a variety of gears, pins, shafts and similar engineering details, with, perhaps, some non-ferrous alloy sheets or sections. Special furnaces have been developed for these purposes, the usual source of heat being either coal gas or electricity.

Furnaces arranged to burn coal gas have undergone vast development in recent years. Efforts to improve the thermal efficiency have led to both improvements in design and in burners. The thermal insulation of the furnace has greatly cut down heat loss from walls and roof, good engineering design

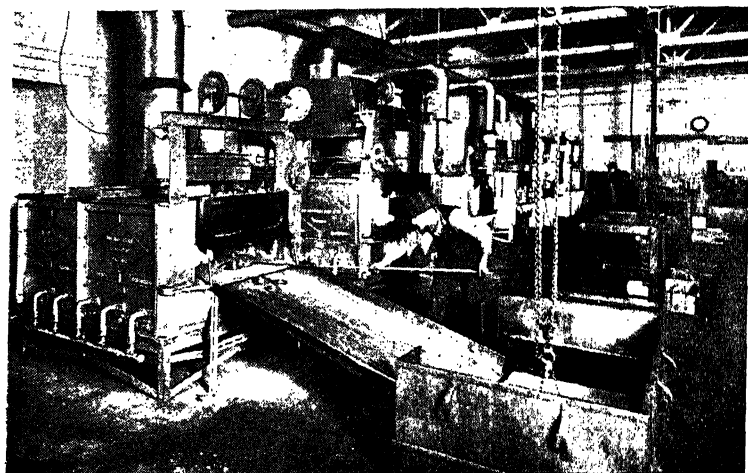


Fig. 8.—A battery of six heat treatment and carburising furnaces operating on standard town gas supply, suitable alike for annealing, reheating, normalising, preheating, tempering, carburising, etc. Temperatures up to 1100°C . may be obtained.

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has perfected working doors which are easy to manipulate and do not waste heat, burners have been vastly improved and recuperation introduced, resulting in further heat saving, while the extensive use of the newer heat resisting alloys in the interior construction of the furnace itself has paved the way for mechanical handling of charges. The great disadvantage of the older type of gas furnace was the total lack of control of the furnace atmosphere. In cases where the nature of the furnace atmosphere was of the utmost importance (as in most heat-treatment) the gas furnace could not compete successfully with the electric form, where the heating chamber could be charged with any desired atmosphere. Recently, however, the newer high-chromium heat-resisting alloys in the form of tubes have been utilised in gas furnaces. These tubes are heated from within, their outer surfaces radiating their heat to the charge, thus establishing conditions in the furnace chamber very similar to those in electric furnaces. Recent improvements have incorporated a recuperator in the tubes, and an ingenious system of burners ensuring perfectly even distribution of heat along the whole length of tube. Fig. 7

gives a diagrammatic representation showing how this type of burner operates. The burner tube at one end burns a gas/air mixture which is deficient in air to the extent of 50%. The remaining air, necessary for complete combustion, enters through the recuperator at the opposite end, is superheated and emerges through a series of small holes along the inner tube. The flame thus develops maximum heat in the area opposite the holes, and because of the recuperative effect, actually results in a gas saving of the order of 15%. A further advantage of this type of burner is that it can be used either vertically or horizontally, thus being in every way as accommodating to furnace designers as the electric furnace. Typical designs of modern furnaces which utilise gas heating for carburising and other heat treatment are shown in Figs. 8 and 9. These illustrations also give a very good idea of up-to-date practice in this country. Incidentally, they show that the heat treatment shop need not, as was formerly supposed, be a dark and uncomfortable part of the factory.

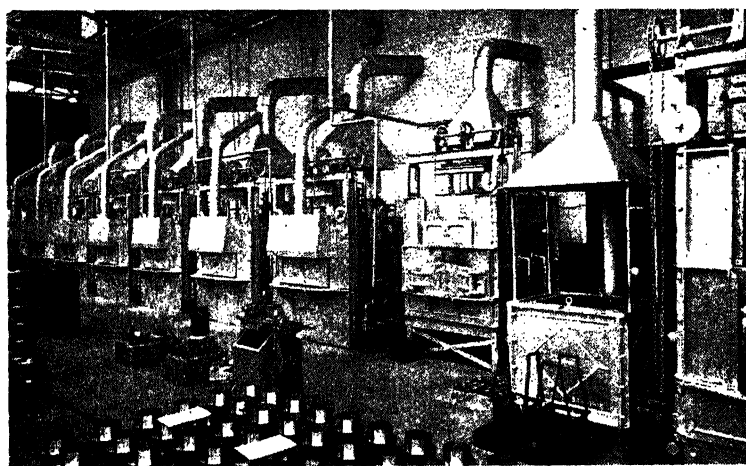


Fig. 9.—Gas-fired recirculated atmosphere furnaces suitable for temperatures up to 550° C. Internal dimensions 4 ft. 6 in. × 1 ft. Fired by a series of patent injector type self-intensifying burners, complete with one automatic thermostatic control valve. An indicating pyrometer is fixed on the side of the furnace

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Electric Furnaces

Electric furnaces of various kinds have long been in use for heat treatment. With the development of reliable nickel-chromium alloys for use as heating elements, their popularity for all kinds of work up to about 1000°C . has increased. Practically all furnaces used for heat treatment, of the electric type, depend for the generation of heat on suitable resistors placed inside the furnace chamber. These resistors become hot with the passage of the current and radiate their heat to the charge. For temperatures up to about 1000°C ., the resistors are usually made of "Nichrome" wire or tape. This material, besides having a high electrical resistance, also stands up very well to high temperature, and cases are on record where furnaces have worked more or less continuously for five years and more without any appreciable damage to the elements

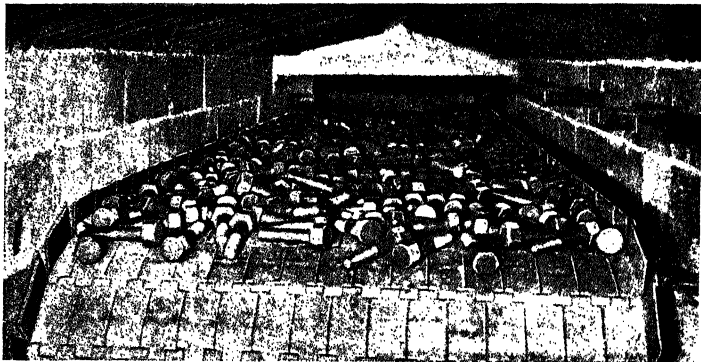


Fig. 10.—Continuous electric furnace showing chain belt laden with bolts

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being apparent. When furnaces are required for operation above this temperature, as in high-speed steel hardening, a more refractory material is used, such as silicon carbide. Naturally, the life of these elements at high temperatures is much shorter, and they are only used for small tool hardening furnaces. Electric furnaces lend themselves very well to automatic control at all temperatures, and generally it is possible to hold a large electric furnace within a temperature range of about 5 degrees with the aid of electrical controllers, working off thermocouples in various parts of the furnace. Thermal insulation

can also be carried to a high pitch of perfection since there need not be any flues, etc., through which heat can be lost. Large furnaces of this kind are ideal for heat-treating a large number of small parts such as gears or small forgings. The internal heating elements are often connected to three-phase supplies with star-delta automatic switching for heat regulation. In large installations, time switches and recorders are standard equipment permitting furnaces to be put on or off at any selected time. This feature is particularly valuable at week-ends, since work can be resumed at the beginning of the week with furnaces already at temperature. Like the

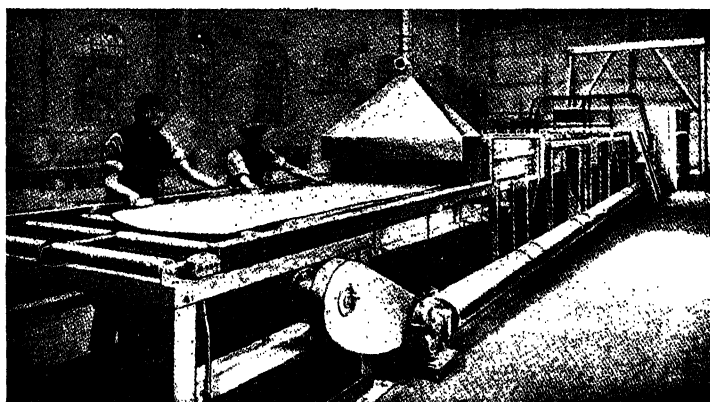


Fig. 11.—Continuous bright annealing furnace

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modern types of gas furnaces, of course, the larger electric furnaces can be adapted to mechanical charging or have mechanical conveyor hearths, constructed of heat-resisting alloy, for continuous work. Special designs are also met with in which the whole furnace can be lifted from the hearth and placed over another hearth containing a fresh load, but these are necessarily of limited application. Figs. 10 and 11 show mechanical types of furnaces designed for special duties. The only attention required in these cases is actually to supervise the loading and unloading, since the temperature and time factors are automatically controlled.

Tempering Furnaces

Both coal gas and electric furnaces are well adapted for low temperature heating of parts of the kind met with in tempering, or otherwise treating steel or non-ferrous alloys in engineering shops dealing with large numbers of small parts. Such operations do not call for high temperatures but the heat distribution must, of course, be uniform in the charge. Furnaces specially designed for this purpose have means, generally a fan, by which the hot furnace atmosphere is continuously circulated

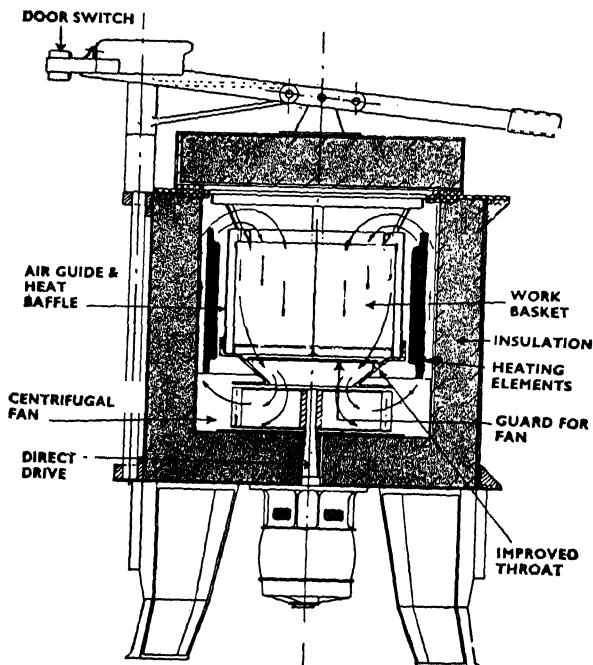


Fig. 12.—Electric forced-circulation furnace for tempering and treating non-ferrous alloys

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over the work. These forced-circulation furnaces are used for a great many low-temperature operations, such as tempering ordinary and high-speed steel and the treatment of various non-ferrous alloys. Fig. 12 shows one very popular type widely used for treating small parts, but larger furnaces are, of course, made for dealing with heavier work.

Other forms of tempering equipment are oil, salt or metal baths. There are many kinds of such equipment available, and, like the higher temperature furnaces, are designed for the particular end in view. For example, oil baths are widely used for tempering various types of tool steel where the tempering temperature does not exceed about 250°C ., salt baths find wide application in the heat treatment of aluminium alloys, and molten lead is often used for the higher temperature tempering of steel. These baths may be heated either by gas burners suitably arranged or by electric heaters of the immersion type. The salt baths, being fairly good conductors when molten, are sometimes heated by the passage of alternating current directly through the bath, when temperatures up to the highest in use are required, i.e., about 1350°C ., the hardening point of high-speed tool steel. Special salts are required for these high temperatures, sodium carbonate being usually the basis of commercial mixtures. While these salts are cheap and readily obtained, the furnaces require a special transformer to step down the voltage of the mains to a low value and deliver the very heavy current required. Direct current cannot be used, since electrolysis of the salts would occur. Another point is that special means must be adopted in starting up from cold, since the salts are only conductors when liquid. This is accomplished by spreading a conducting path of carbon across the surface of the solid bath, the heat generated gradually fusing the salt and thus forming a path for the current. For this reason, such furnaces are better adapted for continuous operation rather than for intermittent use.

Conditioned Atmospheres

As already indicated, the furnace atmosphere has an important bearing on heat treatment and can greatly affect the quality and sometimes even the saleability of the work. Atmospheric air and the various products of combustion are chemically active at high temperatures, giving rise to the familiar forms of scale on many metals. Since it is not practicable, on a commercial scale, to carry out heat treatment of metals in the total absence of gases, i.e., in vacuo, improvement is sought by modifying the nature of the furnace atmosphere.

The most obvious way to minimise scaling is to heat the material in an inert atmosphere, such as nitrogen, this gas

having no chemical affinity for the majority of metals and alloys. Perfect results can only be obtained by this method, however, if the gas is thoroughly dried before entering the furnace chamber, since water vapour is corrosive at high temperatures on most metals. The method, while good in theory, suffers from the disadvantage of being comparatively costly, and for this reason is not often adopted. It is possible, however, to generate atmospheres by simple methods which

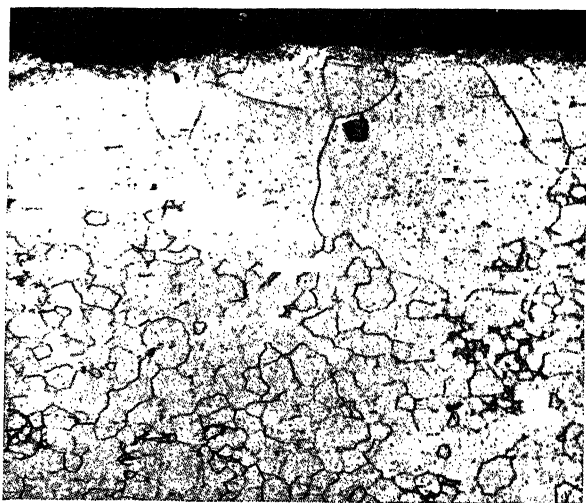


Fig. 13.—Cross-section of mild steel over-heated. Note the large grains at the surface showing the effect of grain growth. This structure is practically pure ferrite. The almost total absence of pearlite indicates that the overheating has also caused considerable decarburisation, the heating having been conducted in an oxidising atmosphere

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give fair protection and fulfil the needs of perhaps 90% of furnace work. Where electric or muffle furnaces are used, it is common practice to place boxes of wood charcoal near the doors. The air leaking into the heating chamber passes over the glowing charcoal and generates carbon monoxide, which, being a reducing agent, helps to minimise scaling considerably. If the doors are reasonably close, the atmosphere of the muffle soon becomes very highly charged with this gas. It should

be noted, however, that since no attempt is made to remove water vapour, both from the ingoing air and that generated by the combustion of hydrogen in the charcoal, scaling will still take place in the majority of cases.

Fig. 13 is a microsection which illustrates the effect of oxidising atmospheres on steel. Here, a piece of mild steel shows complete removal of carbon on the surface. In this particular case the decarburisation is accompanied by grain growth, indicating serious overheating as well.

The modern approach to this problem is to remove the most active gases from such an artificial atmosphere, leaving an inert atmosphere in the furnace. The atmosphere is generated by the combustion of coal gas, the water vapour and carbon dioxide removed from the products of combustion and the remaining inert or reducing gases passed on to the furnace. The water vapour is either condensed or absorbed, and sometimes carbon dioxide is absorbed also in alkaline material. The most recent development in moisture absorbers utilises the hygroscopic properties of specially prepared alumina, which can be readily reconditioned, when saturated, by simple heating. Special units are now obtainable for this purpose. The whole subject of conditioned atmosphere is one of recent development, and several important details are worth noting. In the first place, each metal and each temperature in the furnace will alter the chemical characteristics of a given atmosphere. A gas mixture which may be inert to one metal will not necessarily be inert to all metals. For example, hydrogen will protect copper efficiently at high temperatures and water vapour (highly superheated steam) has no effect on hot copper. Steel at high temperatures, however, can be badly decarburised by hydrogen and highly oxidised by water vapour. The decarburising effect of hydrogen on steel is not widely appreciated in heat treatment plants, but it can easily be demonstrated that prolonged annealing in an atmosphere containing a large amount of hydrogen produces a decided decarburisation on the surface of steel. The reaction proceeds thus: $\text{Fe}_3\text{C} + 2\text{H}_2 = \text{CH}_4 + 3\text{Fe}$, the carbon escaping as the gas methane (CH_4).

As indicated, the nature of the material influences the effect also. The temperature at which scaling begins generally rises in steels as the alloy content increases. The stainless and rustless and, of course, the allied heat-resisting steels, which are all highly alloyed, can resist higher temperatures and more

oxidising atmospheres than the plain carbon varieties. It will thus be seen that some variable control of the composition of the furnace atmosphere is desirable to meet whatever end is in view, the exact composition being a matter of some experiment. Modern designs of furnaces give full control over the composition of the atmosphere and are thus adaptable to practically any requirements. The most elaborate modern furnaces are now capable of heat treating highly finished metal parts on a continuous basis without even tarnishing the metal.

Pyrometric Control

At the outset it was stressed that accuracy of temperature in heat treatment was of vital importance, and it will not be out of place now to consider the means adopted commercially to obtain this. The most widely used pyrometer, for the higher temperatures at least, is the base metal thermocouple. This is essentially two wires of dissimilar metals or alloys (usually the alloys "Chromel" and "Alumel") welded together at one end, and connected, by means of suitable extension leads, to a sensitive galvanometer. On the welded end being heated, a potential difference is set up which affects the galvanometer. This potential difference is only of the order of perhaps 30 or 40 millivolts, but is proportional to the temperature, and the galvanometer can accordingly be calibrated to read degrees directly. This is the simplest form of high temperature thermometer, and as such is widely used to check the temperature of large work when the furnaces are manually controlled. The upper limit of temperature which can be measured by these base metal couples is about 1100° C., but similar couples of platinum-platinum with 10% rhodium can be used up to about 1500° C. Coal gas furnaces and electric furnaces, however, are readily adapted to automatic control, and when these are set up for production work, the thermocouples are usually connected to automatic recording and control gear, thus ensuring that the furnaces will remain steady, within a very few degrees, at any selected temperature. Hot liquid baths can also be arranged for this type of control. Large plants which maintain a continuous output of carburised and heat-treated parts are invariably fitted with control gear of this type, since it would be virtually impossible to maintain uniform results without its aid.

Quenching Liquids

While much has been said regarding furnaces and other equipment, the cooling of the heated parts is also of some importance. Quenching steels for hardening or refining depends for its success in no small measure on the technique adopted. The most drastic cooling rates are obtained in water or various aqueous solutions, and rather milder quenches in oils. The initial temperature of the quenching liquid and its velocity or degree of agitation, also influences the final result. The table below shows the effect of temperature and other materials in water. The various liquids are tabulated in decreasing order of effectiveness:

Liquid						Temperature
5% caustic soda	...	...	...	...	...	20° C.
10% salt	...	...	...	...	...	20° C.
Pure water	...	...	...	...	...	20° C.
" "	...	...	...	...	...	40° C.
" "	...	...	...	...	...	80° C.*
" "	...	...	...	...	...	100° C.

* Equivalent to most oils at 20° C.

Although, as pointed out above, water at 80° C. is equivalent to oils, in some respects oil and water quenching differ considerably. The high heat capacity of water makes itself felt as the steel cools down to moderate temperatures in a manner not exhibited by oil, and consequently water-quenched steel is likely to have more internal strain set up unless definite steps are taken, such as removing the piece before it is quite cold or tempering immediately. Failure to appreciate this simple point often leads to otherwise inexplicable cracking and distortion.

The practical methods adopted in quenching vary with the class of work undertaken, of course, but the general arrangement consists of a suitable tank to hold a considerable volume of the liquid, thus ensuring that the bath as a whole will not alter in temperature appreciably during quenching. A circulating pump, often of the "suds" type fitted to machine tools, helps towards maintaining even temperature throughout the tank, and where the amount of work being dealt with justifies the equipment, cooling coils are introduced. In the largest oil tanks, a common cooling system is to circulate the oil through a heat exchanger cooled by a large fan. In places where cold

water is cheap and plentiful, this is also used for cooling the oil in some form of heat exchanger. Like water, oil rapidly loses its effectiveness the hotter it becomes, and consequently it is of the utmost importance to maintain quenching tanks at as low and constant a temperature as possible. To guard against fire risk, and for the comfort of the workmen, quenching oils should have a high flash point, certainly not less than 200° C., and should be stable over long periods of use. Some oils have a tendency to become "gummy" after some use. In this condition, quenching efficiency falls off rapidly.

CHAPTER III

Casehardening

The object of casehardening is to produce a hard surface on steel while leaving the core relatively soft. Such parts as gears, shafts, spindles, etc., in general require a hard, wear-resisting surface only, and their properties are improved, from an engineering point of view, if they can be made at the same time ductile and tough enough to resist torsion or other localised stresses. For this type of work, various casehardening processes offer a ready solution to the problem. The processes to be described are surface-hardening processes only, and it is rare to find commercial practice aiming at greater than about 0.050 in. depth of hardening from the surface. Only in the carburisation of large armour plates is this depth greatly exceeded, but since this is a highly specialised process of limited application it need not be considered here.

The most important and widely used commercial processes carburise the steel surface in order to produce the desired hardness. As has been stated already, gamma iron forms a solid solution readily with carbon, while alpha iron for all practical purposes does not. If steel is therefore heated over its upper critical point in presence of carbon or carbon compounds, the carbon is readily absorbed, and after some time at this elevated temperature the surface becomes quite rich in carbon. The surface, in fact, approaches the composition of a tool steel and as such, of course, is hardenable by quenching. It is possible to cause this progressive absorption of carbon with a wide variety of carbonaceous materials. For example, gases containing high percentages of carbon compounds, such as coal gas, oil gas, acetylene, etc., can react with steel and carburise it quite satisfactorily. Of the solids such materials as wood and bone charcoal, leather clippings and the like are widely used, while so-called "energisers" may be added, the most popular being barium carbonate and soda ash (sodium

carbonate). Fused salts containing carbon are also frequently used, principally cyanide of sodium or potassium.

The process itself is usually a somewhat lengthy one. The carbon, in whatever form it comes in contact with the hot steel, first of all combines with the iron to form the carbide Fe_3C . This carbide is then taken up to form the gamma solid solution, and diffuses to some extent into the surface layers of the metal. The time factor is influenced to some extent by the nature of the steel, as is also the final depth of carbon penetration. Since the diffusion of the carbide is through a relatively immobile solid, it is necessarily a slow process even under the best conditions. The rate of diffusion is influenced considerably by the temperature, increasing temperature accelerating the process, but the character of the case is also influenced, and this consideration, in practice, sets an upper limit to the working temperature.

Without going into the debatable theories which have arisen at various times as to how the carbon is carried to the steel from the medium, it can be stated that the modern conception of this reaction is that some gas must be present to act as a carbon "carrier," and this gas is probably carbon monoxide (CO). Oxygen, either derived from the atmosphere or artificially provided, combines with the carbon to produce this gas which then reacts with the iron. The following equations show the essentials of the reactions:



The oxygen, shown liberated in equation 3, immediately combines with more carbon to form, ultimately, the monoxide, and thus the cycle repeats itself. At the carburising temperature the carbide is absorbed as it is formed. An important factor in this cycle of reactions is the rate of diffusion of the carbide into the gamma solid solution. The chemical reactions by which the carbide is formed are considerably accelerated by rising temperature. The rate of diffusion through the solid solution is similarly accelerated, but a point is very soon reached when the carbide is formed faster than it can diffuse. Free carbide begins to appear on the outside layers, and although this is a hard constituent, it is brittle and is the cause of much of the "spalling" observed on carelessly hardened

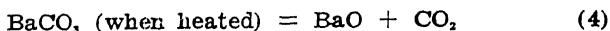
work. Both high temperatures maintained during the process and highly active carburisers, in a chemical sense, can lead to this result with disastrous effect on the work. The practical effect of these conclusions is that, all other things being equal, the best results are obtained with the lowest working temperature. The depth of case obtained is then a function of the time and is thus amenable to some degree of control.

Practical Processes

Perhaps the most widely used, and certainly the oldest process, is surface hardening using solid compounds. As already observed, very little solid carbon can be absorbed by steel, but certain chemical reactions give rise to products which act as "carriers" of carbon to the metal. The principal carrier appears to be carbon monoxide, although the presence of solid carbon or carbon compounds undoubtedly increases its effectiveness greatly. Pure charcoal itself can be classed as a mild carburiser at the usual working temperatures and carburises slowly. It gives well-graded cases, however, when the carburising time is long enough to give fairly deep penetration. The commonest form is made from wood, chiefly on account of its low sulphur content, since sulphur in the carburiser is likely to be absorbed by the steel and is undesirable on that account. Animal charcoal is also frequently used as well as various mixtures of both. These mixtures appear to be more active and rapid in their effect, although all are mild and show no tendency to build up thick cases under ordinary commercial conditions. The volatile hydrocarbons which are present in the animal charcoals intensify the carburising effect of the wood charcoal, and consequently such mixtures find their greatest application for producing thin, moderately hard cases.

Of the more active solid carburisers the barium carbonate-wood charcoal mixture is perhaps the best known. It is also one of the best mixtures for general use and forms the basis of many commercial compounds. It is usually made up by mixing the finely powdered components thoroughly in the proportion of 40% of the carbonate and 60% of the charcoal by weight. Hard beech charcoal is best for the purpose since it is denser and does not burn so readily. The mixture is often incorporated with a binder and formed into granules, since it is easier to handle in that form and more economical for packing into the boxes. Carbonate of soda is also frequently present

in commercial mixtures. The action of the carbonates is to generate a plentiful supply of carbon monoxide according to the following equation:



Thus a box packed with such a mixture will always be well charged with carbon monoxide.

So far, nothing has been said as to how the carbon distributes itself in the surface layers of the steel. This depends on the temperature at which the process is carried out, but whatever temperature is selected, every endeavour should be made to obtain a gradual diffusion of the carbon, and modern practice using energised carburisers usually adheres to not more than 100° C. above the upper critical point of the steel. To avoid free carbide, with its associated dangers of spalling and cracking of the surface, it is also wise to limit the surface carbon to the eutectoid amount (0.85%). As will be seen later, this practice also simplifies subsequent heat treatment.

The practical details of the process consist of packing the pieces to be hardened in boxes containing the carburising mixture. The boxes should be packed in such a way that about 1 in. of compound surrounds each piece in every direction. For odd work, the boxes may be of cast iron or steel and provided with a close-fitting lid. Quite efficient boxes are sometimes made from scrap steel sheets or tube assembled by welding, the covers being luted on with clay. In plants where case-hardening is on a production basis, however, it is more economical in the long run to use special boxes made of heat-resisting alloy, usually of the nickel-chrome type. These boxes retain their shape and can be effectively sealed even after very long heating. By thus preventing adventitious leaks, burning of the compound is avoided—a source of much needless loss of compound when using warped and distorted containers.

When the boxes are packed they are charged into the furnace and, after raising to the required temperature, held for a number of hours, depending upon the depth of case required. For example, carburising mild steel at 900° C. would require perhaps 6 hours to give a depth of about 0.040 in. In this connection it may be well to remark here that 0.050 in. case depth would be regarded as a deep case for most commercial purposes and would only be given to jobs requiring the utmost

strength and hardness, such as automobile gears and similar heavy duty applications. The time, however, is a very variable factor, and no hard and fast rules can be given, depending as it does on the activity of the mixture and the time taken for the job to reach the carburising temperature.

Fig. 14 illustrates the influence of both carburising temperature and time on the depth of case obtained with a low energy compound. The graphs show how predictable results may be obtained once the characteristics of a compound have been established.

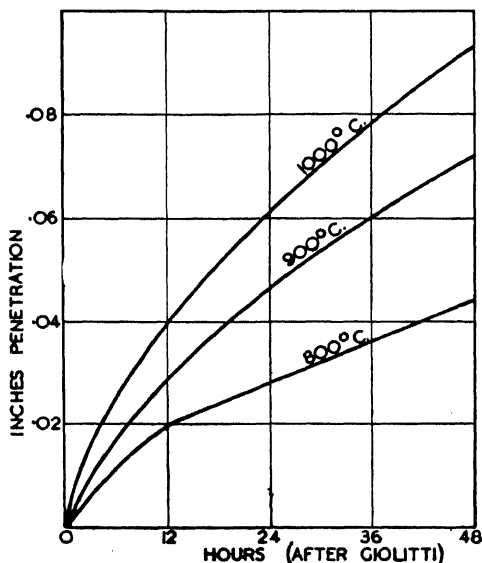


Fig. 14.—Influence of carburising temperature and time on depth of penetration using a low energy carburiser

Common practice is to place a few test-bars in the boxes along with the charge and judge the progress of the process by withdrawing them at suitable intervals. These bars are "nicked" and broken, the fresh fracture revealing the penetration of carbon. The fractured face may also be ground flat, polished with fine emery and etched in a 10% nitric acid in alcohol solution, when the carburised area is revealed by being more darkly coloured than the main mass of the steel. When the carburising is judged to have gone far enough, the parts may be quenched

directly from the box, but generally this is only done with unimportant parts and, metallurgically, is bad practice. Steel which has been heated for a number of hours at temperatures over A_c , will be extremely coarse-grained and usually brittle. It is desirable, therefore, that the steel should be cooled out

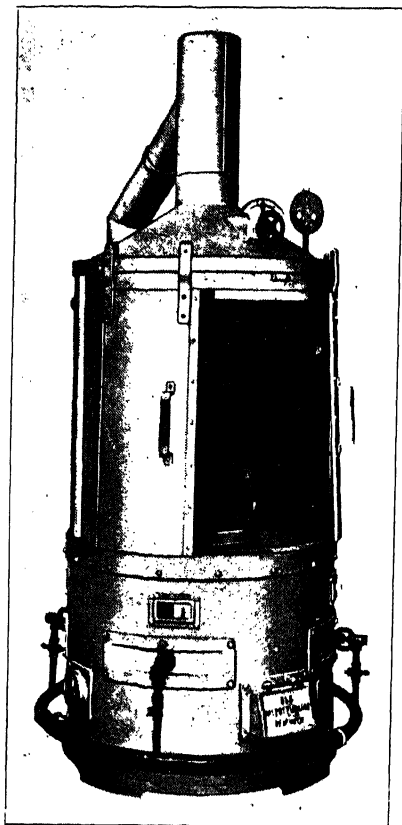


Fig. 15.—G.L.C. small town-gas-fired pot furnace. Suitable for cyanide hardening

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and subsequently heat-treated to remove this brittle structure as well as to harden it, and it is poor economy to try to save time by omitting this procedure.

It sometimes happens that only parts of a job are required to be hard. In this case the soft areas can be sealed off from

the carburising action of the compound by special "anti-carburising paste," or they can be copper plated. For stopping-off holes, etc., the paste can be advantageously used, or they can be plugged with ordinary clay. The copper plating is put on in a cyanide plating bath and is better adapted for repetition work. There is yet another method which can be adopted. If the soft parts are machined oversize before carburising, the high carbon case can readily be removed when bringing these parts down to size before the final heat treatment. This method is frequently used in production, since it only involves a simple machining operation, and consequently is to be preferred in repetition work to hand operations such as plating or painting with paste. It will be appreciated, however, that the method adopted depends greatly on the design of the part in question as well as on the number which will have to be produced.

Cyanide Process

One other casehardening process of commercial interest remains to be discussed. The cyanide process uses fused sodium or potassium cyanide (NaCN) as the "carbon carrier." It has the merit of simplicity and does not require extremely elaborate furnace equipment. The salt is simply fused in a pot held at about 900°C ., at which temperature it is thoroughly liquid. The parts to be hardened are immersed in the liquid for about one hour, withdrawn and subsequently heat-treated (Fig. 15). While the process itself is straightforward enough, some very necessary precautions must be taken. The cyanides are highly poisonous and the fume from the molten salt is also deadly. For this reason the pot must always be covered by a hood and have an efficient extractor to protect the workmen. Men working about the furnace should always wear thick gloves and a mask to protect the face from accidental splashing of the salt. For this reason also parts should be well warmed and dry before introducing into the bath. The preheating of all parts is beneficial in any case since it obviates thermal shock and minimises cracking and distortion. A preheat to, say, $300^{\circ}\text{--}400^{\circ}\text{C}$. will not cause scale and will save time in the bath. In order to suppress the poisonous fumes to some extent, the cyanide may be mixed with about 10% of either common salt or sodium carbonate. Thin cases can be produced by half-an-hour in the mixture, and since the heat is only maintained

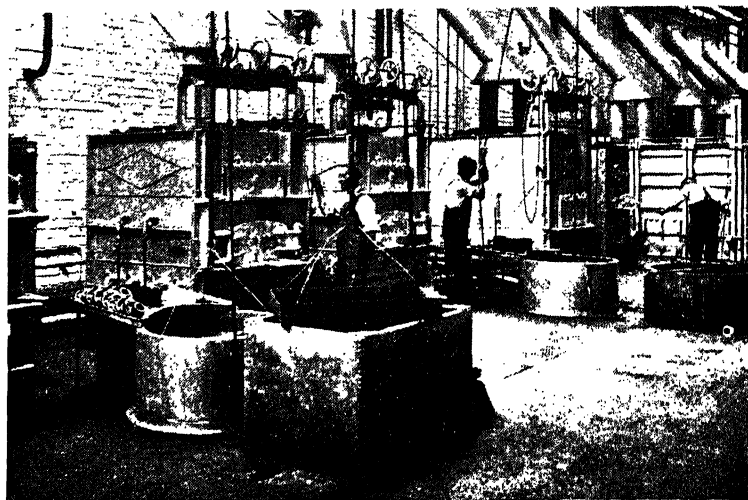


Fig. 16.—Double deck furnaces for refining the core of carburised components by soaking them at a temperature of 900° C. and then quenching in oil. Also used for the production of the hard case on carburised components and the hardening of non-carburised components. The upper chamber is used for preheating to avoid unduly rapid heating which might result in distortion and cracking of the components

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for such a short period, the grain of the part will still be reasonably fine. Consequently it is permissible to quench directly from the bath for hardening. Since the parts in the cyanide pot are immersed in a liquid, special care should be taken to avoid distortion. Long slender rods should be stood vertically in the pot to avoid sagging under the influence of the heat. Small articles are frequently placed in baskets and suspended in the liquid. Both the containers and the pot itself, of course, are made of heat-resisting alloy.

The cyanide process finds its widest application in the hardening of small parts, such as pins, screws, cams and similar pieces where a high surface hardness is rather more important than great depth hardness.

Steel for Casehardening

A steel, to be suitable for casehardening, must fulfil two functions:

(a) It must be soft and tough.

(b) It must take a high surface hardness when carburised and heat-treated, without cracking or distortion.

Condition (a) limits the choice to low-carbon steels, and in practice the maximum carbon of the steel before carburising is seldom above 0.20%. It can advantageously be much less, but this governs to some extent the maximum core strength obtainable. Condition (b) imposes a practical limit on the manganese content of the steel. For casehardening steels which have to be water quenched for hardening, high manganese content makes the high carbon case unduly sensitive to cracking. Consequently the simple carbon and low alloy steels in this category are preferably kept to rather low limits for manganese. A good working rule is to keep the manganese down to 0.5% maximum. Typical compositions are given below :

TABLE I

B.S. Spec.		C.		Mn.		Ni.		Cr.		Mo.
2S14	...	0.15	...	0.45	...	—	...	—	...	—
3S15	...	0.12	...	0.50	...	3.0	...	—	...	—
S90		0.16		0.50		5.0				
S82		0.14		0.50		4.25		1.25		0.40

All the above steels are quite suitable for casehardening by any method, and while there are many other steels which have been developed for special purposes, these standard specifications enjoy well-deserved popularity among engineers.

Heat Treatment

The heat treatment of carburised work now falls to be considered. As already stated the carburising temperature should be as low as possible consistent with being above the upper critical point of the steel. A glance at the iron-carbon diagram will show that for a plain carbon steel with about 0.15% carbon, this point lies about 800° C. The effect of nickel on the steel is to lower this point, and consequently it will be found that the recommended temperatures for carburising and other heat treatment of such steels is rather lower than for the corresponding carbon steel. As to the actual carburising temperature, there is some room here for choice, but for general work good commercial practice appears to be in the neighbourhood of 890°-920° C. This gives reasonable carburising speed and, provided that the compound is not over energetic or the time too prolonged, will give good results.

When a piece of steel has been carburised properly it may be considered as consisting of two steels, viz., a soft low-carbon core and a high-carbon "skin." The hardening treatment should thus be designed to place both these steels in the best physical condition at the same time. After prolonged heating at high temperature, grain growth will have coarsened the original steel as well as the high carbon case, and the first step is to refine the core before going on to refine and harden the case. Assuming that the part has been cooled in the box after carburising, the procedure would be to re-heat it to a temperature just over the upper critical point of the soft steel. A common type of furnace for this purpose is shown in Fig. 16. At this temperature the transformation is passed which obliterates the original coarsely crystalline structure, and on cooling after being held at this temperature for just long enough to complete the transformation, the core will be re-crystallised in its finest and toughest form. This first refining heat, however, will have considerably overheated the high carbon case, since the transformation point of, say, 0.85% carbon steel, is far below that of the core containing only perhaps 0.15% carbon. To refine the case, then, the steel is heated once more to the lower hardening temperature of the 0.85% carbon steel and quenched once more. This second lower temperature has no influence on the already refined core, since it is far below its transformation point where grain growth commences. In the common low carbon and low alloy casehardening steels it will be observed that this double treatment is recommended, and it is always employed in the highest grade work. If it is neglected there is always the risk of premature failure of the parts. The following table sets out the hardening scheme for the steels given in Table I, and represents commercial practice. The alloy steels are adopted because they admit of some simplification of heat treatment.

TABLE II

B.S. Spec.	Refine °C.	Harden °C.	Max. Stress Tons/in. ²	Izod ft.-lb.
2S14	900 W.Q.	780 W.Q.	about 30	about 60
3S15	860 O.Q.	770 O.Q.	53	62
	860 O.Q.	770 W.Q.	61	45
	Omit	770 O.Q.	51	60
S90	830 O.Q.	760 W.Q.	80	33
	830 O.Q.	760 O.Q.	69	48
	Omit	770 O.Q.	68	45
S82	830 O.Q.	760 O.Q.	88	38
	Omit	760 O.Q.	87	32

NOTE.—"W.Q."—water quench. "O.Q."—oil quench. Physical results obtained on 1½-in. bars.

The above table shows how alloying elements can modify the heat treatment and counteract the effect of mass. The impact value is some measure of the brittleness of the material after each heat treatment. It will be observed that even omitting the preliminary refining in the nickel steels does not have the same disastrous results as it would have in the simple carbon types. Part of the explanation of these facts is to be found when it is considered that nickel is an excellent grain growth inhibitor, and when present in steels in amounts above 3% they can stand prolonged heats at high temperature without great damage. Carbon steels, on the other hand, coarsen rapidly under these conditions, making the refining heat imperative. They have the advantage, however, that as a rule the cases develop greater hardness on water quenching, but the limit of their usefulness is reached when the relatively soft core begins to crush under load. For this reason the alloy steels are preferred, having a harder core, for high duty.

Parts of complicated design are also usually made in alloy steel because of their lower hardening temperatures helping to minimise warping. The ability to omit the higher refining heat is also of value in such cases.

No matter whether the simple carbon or alloy steels are used the rough forgings or bars should always be normalised before machining. This simple precaution often results in a marked reduction in distorted work after carburising. It is also beneficial in cases where much heavy machining has been done on the parts to give a short "tempering" heat at about 350° C. with a view to relieving machining stresses. After this treatment any slight distortion can be corrected by cold setting.

A frequent trouble is fine cracking revealed after grinding. This is often caused by brittleness of the case. Much of the cracking of this nature can be avoided by tempering after hardening and a final tempering treatment is strongly recommended. Heating for one hour at 160° C. will not cause any appreciable change in the hardness of the case and will often avoid what are mistakenly taken for grinding checks. Overheating during grinding will also cause cracking, but such cracks arise from carelessness and should never occur in a properly equipped machine shop.

Fig. 17 shows a somewhat unusual application of carburising, and is interesting in showing how valuable material can sometimes be saved. This also illustrates an aspect of tool

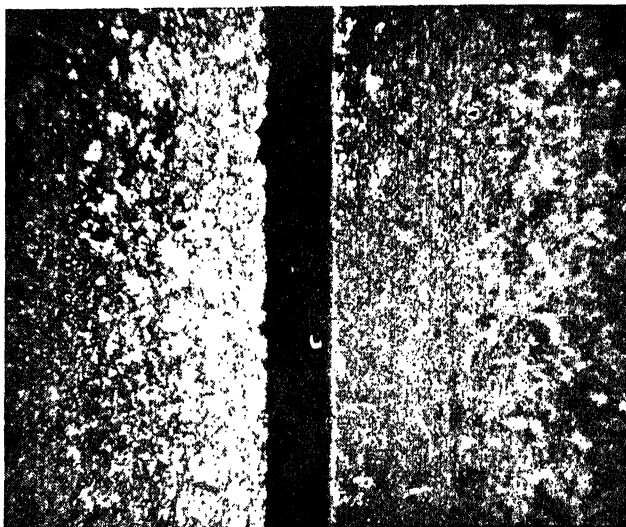


Fig. 17.—High carbon (0.85%) bar. Cross-section showing surface decarburised after rolling (left), and same bar recarburised by cyaniding (right). This is a rather unusual application of case-hardening

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hardening practice, where decarburisation of the surface is particularly undesirable.

Nitriding

Another surface-hardening process depends on the absorption of nitrogen into the steel. In this case special steels are used, the principal requirements being the presence of some or all the following elements in the steel: aluminium, chromium, molybdenum and sometimes vanadium. Contrary to the carburising practice, the initial steel may be quite high in carbon content, thus allowing a strong core to be obtained. It is desirable that the steel should be in the sorbitic condition before treating with the nitrogen, and a preliminary heat treatment is given with that end in view. The usual programme is to quench the steel in oil from 900° C. and, when cold, to draw at about 680° C. The machining operations are then performed, taking care that all surface material is removed and with it any decarburised metal. If the steel is badly de-

carburised, excessive brittleness and growth occur on these areas on nitriding. After machining, a further heating for a short period at about 500° C. is given to remove all strain. This heat can advantageously be given in a conditioned atmosphere furnace to avoid scaling. The parts are then ready for the nitriding treatment. They are packed in a special container using nickel grids, the whole being carefully sealed off, and ammonia gas circulated through the box. The box is heated in a furnace at about 580° C. for a period depending on the depth of case desired, usually about 48 hours for, say, 0.030 in. The finished surface after cooling off in the box requires no further treatment, and is much harder than a similar carbon case. When the ammonia is passed through the box it is "cracked" into nitrogen and hydrogen, the nitrogen com-

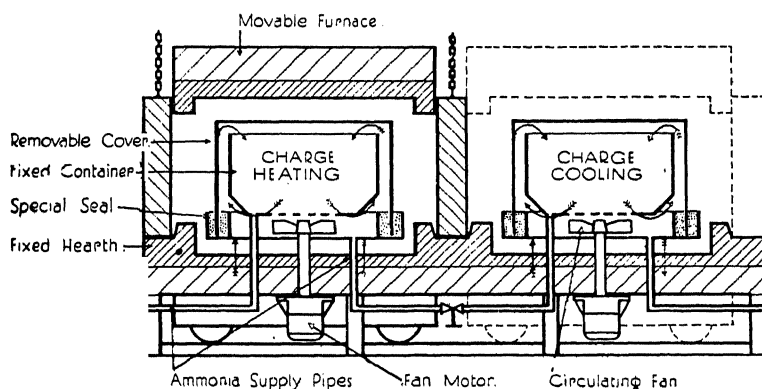


Fig. 18.—Special nitriding furnace. The furnace is movable to allow of continuous operations

Birmingham Electric Furnaces Ltd.

bining with the iron to form the extremely hard and non-brittle nitride which confers the hardness on the surface. Some typical nitriding steels are given in the table.

TABLE III

C.	Al.	Cr.	Mo.	V.
0.25	1.2	1.2	0.20	...
0.35	1.2	1.2	0.20	...
0.25	1.2	—	0.80	...
0.30	—	1.5	0.50	0.50

During this treatment the material swells somewhat, the usual growth being of the order of 0.001 in., but in most cases

this can be disregarded. It may cause distortion, however, if some parts are stopped off, *e.g.*, by tinning to prevent nitriding. Long shafts whose keyways are thus protected often warp due to the pull of the nitrided surface. If warping should occur the parts may be straightened by heating to the nitriding temperature and gently hammering, since the case does not soften on heating. This treatment is preferable to cold straightening. A cross-section of a continuous furnace plant arranged for nitriding is shown in Fig. 18.

CHAPTER IV

Hardening Machines

Apart from the various casehardening processes which have been in use for many years in the surface hardening of steel, other more recent processes have been developed with the same end in view, and are in common use to-day. These processes aim at producing the necessary surface hardness by a straightforward heating and quenching cycle on the surface without the aid of high carbon layers. Two commercially successful processes of this type will be discussed here. In one, the "Shorter" process, the heating is carried out by means of high temperature oxy-acetylene jets traversed over the surface mechanically, while in the other, the "Tocco" process, the heat is generated electrically on the surface by induction from suitably disposed coils carrying heavy high-frequency currents. In both cases, the steel is hardened on attaining the proper temperature by means of high-pressure jets of water.

Before going on to a description of each process and its equipment, it may be well to consider the metallurgical principles common to both processes. In both cases it is desired to produce a hard layer, probably not more than $\frac{1}{8}$ -in. thick, on the surface of the work. This layer, to have good mechanical properties, should be hardest on the surface, and the hardness should gradually merge with that of the core, which will be relatively soft. Any abrupt change in hardness will, of course, be a line of weakness, and may lead to breakdown of the hardened surface. The steel to be hardened in this manner should, therefore, be one with good hardening characteristics, and may be either plain carbon or alloy composition, depending on the core strength and hardness required. Since no carbon is added to the surface in either process, it will, of course, be clear that the carbon content of the steel should be sufficient to allow it to be fully hardened by heating and quenching.

The hardening characteristics of the steel are also affected by its "inherent grain size." This is controlled by the steel

maker and cannot be altered after the steel is cast, since it depends on the manufacturing methods adopted. The steel can, however, be graded by laboratory tests (McQuaid-Ehn Test) and a suitable "grain size" figure allotted to it. In surface hardening by this method, it has been found that a shallow hardening steel, that is, one which does not readily harden right through its mass, is desirable. Such steels, in spite of

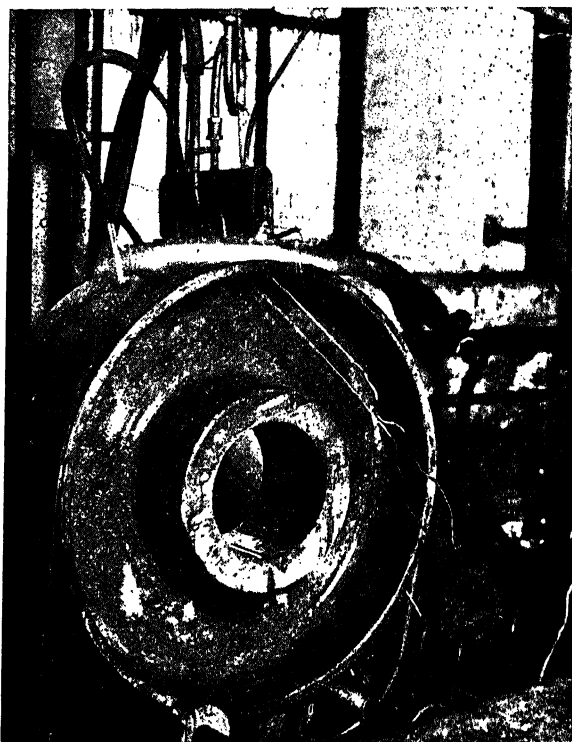


Fig. 19.—A 30-in. dia., 12½-in. face electro mechanical brake-drum being surface hardened by the Shorter process

their shallow hardening characteristics, are tougher and show less tendency to distort than steel with deep hardening characteristics. Deep hardening steels are coarse grained, while the fine-grained steels are relatively shallow hardening. Accordingly, for the purpose of surface hardening, a comparatively fine grain type of steel is used. Extreme fine grain is

undesirable, however, since such a steel would be likely to have many soft spots after quenching. Practical experience points to a grain size of 7—8 on the McQuaid-Ehn scale as being about the best for this type of work. Fortunately, most steel producers work within this range for the greater part of their output and only depart from it when specially required to do so. Incidentally, this desirable grain size corresponds to about 100 crystals in an actual area of 1/10,000 sq. in.

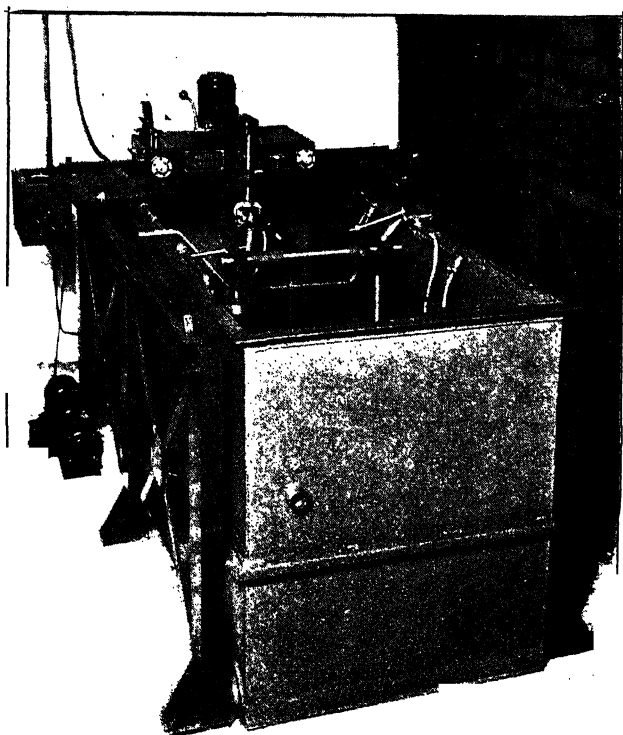


Fig. 20.—General view of a modern Shorter surface-hardening machine. It embodies improvements which simplify operation and provides robust equipment

Since the heating cycle in these processes is comparatively brief, the steel should be in such condition that it will respond promptly to the treatment. In other words, the pearlite constituent should be in as fine a state of division as possible before

treatment so that it will form the solid solution necessary for complete hardening in a short space of time. The usual procedure with carbon and low-alloy steels is to normalise before hardening, while the higher alloy types are sorbitised by a suitable hardening and tempering operation. This preliminary treatment can be carried out on rough forgings and is advisable in any case prior to machining, for obvious reasons. This treatment can be given in a simple type of furnace since the usually generous allowance for subsequent machining obviates the necessity for control of atmosphere.

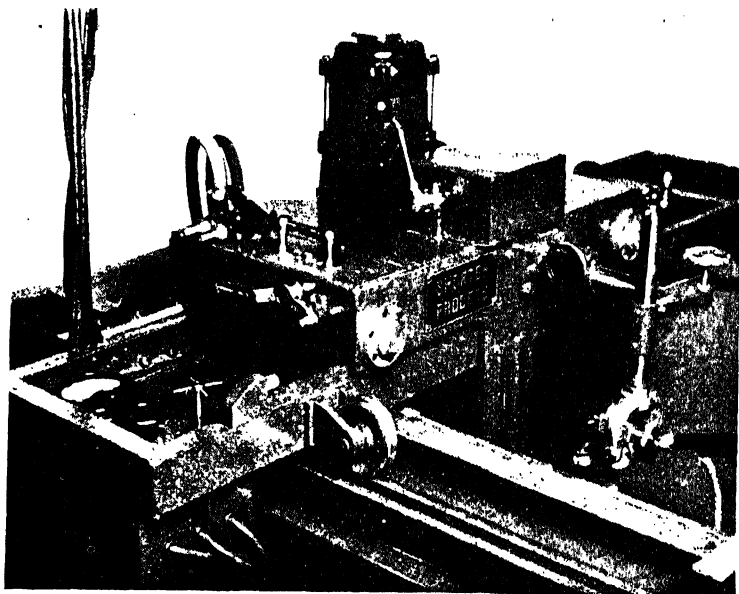


Fig. 21.—The carriage of the Shorter machine shown above. By means of a secondary mechanism worm-gears and other cylindrical parts may be treated

Another advantage of grain refinement by normalising or sorbitising is that the gradation of hardness from the surface inwards is much more uniform than would be the case were the forgings treated as they left the hammer or press. In this way, the risk of the hard surface parting from the soft core under impact or abuse is very much reduced.

Aside from these purely metallurgical considerations, some mechanical points are also worth mentioning. The rate of

heat input to the work should be such that while the surface layer is raised to perhaps 800°C . the bulk of the core is scarcely warm. Obviously, this rate must be extremely high and can only be obtained by a very hot gas flame such as the oxy-acetylene, or electrically by a very heavy transfer of power in a short time. These two principles are the basis of the processes about to be described.



Fig. 22.—Group of cams treated by the Shorter process

Apart from the actual rate of heating, the uniformity of heating is also important. If the penetration of the heat is irregular the hardness will be likewise irregular and, moreover, considerable stresses will be set up on the surface so treated. The practical result of this condition is that the hardened surface sooner or later cracks or even spalls off in parts. Consequently, a prominent feature of hardening machines is the provision made to ensure perfectly even hardening. In cases where the work is traversed under the flame or vice versa, special care is always taken that each part of the surface receives exactly the same treatment.

Attempts to carry out this process by hand usually are failures, since it is quite impossible to regulate the heat sufficiently accurately even supposing that the operator is highly skilled, and accordingly mechanical aid is imperative, although in some cases this may be of quite a simple type. In the electrical process the heat is transferred from suitable coils and is naturally quite uniform over the area covered.

The Shorter Process

The Shorter process is a "gas" process, that is, the oxy-acetylene flame is used as the heat source. There are many variations in the method of application of the heat and the subsequent quenching, but the usual method is to have one or more special burners heating a definite area of the work (Fig. 19). The work is rotated under the flames at a regular speed so adjusted that the surface just becomes sufficiently hot to harden effectively when quenched by the following water jets, which

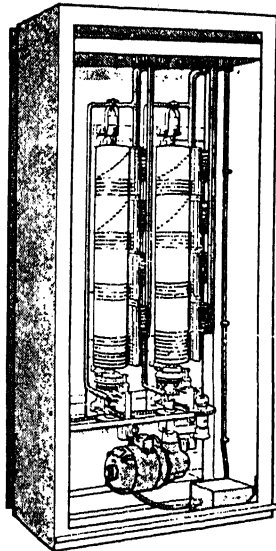


Fig. 23.—Control cylinders for treating crankshafts by the Tocco process. Once a cylinder has been prepared for a given specification it can be used in the machine at any time duplicate parts are to be treated

are suitably placed, and direct a stream of high-pressure water on the steel as it leaves the flame. In some cases, the burners are arranged in ring formation with the quenching jets similarly disposed. This assembly is then traversed over the job, which is itself rotated. Another variation is used on gear hardening machines; here the burner and water jets traverse the flanks of the teeth in a regular manner, every flank being separately hardened. The job is set up in a special water tank

so arranged that only the parts being hardened at a particular instant are exposed to the heat, the remainder of the wheel being under water. These various methods of application are, of course, incorporated in the different types of machine made for varying classes of work (Figs. 20 and 21).

The steel used for hardening by this method should be "hardenable," i.e., if plain carbon it should contain not less than, say, 0.30%. As the carbon content increases, the hardness obtainable increases, the usual range being from about 400 to 850 or more on the Diamond Hardometer scale. The process is applied to the lower carbon range of steels mainly with a view to increasing wear resistance by a substantial increase in surface hardness, while the higher carbon group of steels which are capable of reaching maximum hardness are extensively employed for gears, cams, worms, etc., and are usually hardened on a production basis (Fig. 22). Alloy steels can also be hardened by this process, provided their carbon content is high enough to render them "hardenable," and the usual varieties of nickel, nickel-chrome and other heat treatable alloys can be successfully dealt with. Generally speaking, the presence of alloys causes the effect of the flame to go deeper than in the plain carbon steels under similar conditions, while the untreated core is, of course, tougher and stronger. For this reason, alloy steels are often preferred by designers, especially in cases where weight must be kept down. The superior strength characteristics of the alloy material permit substantial reduction in size.

This process has been singularly successful in the treatment of admittedly "difficult" components. As an example, the automobile starter gear ring is notoriously difficult to harden in the ordinary way, since quenching, even in oil, causes considerable distortion because of the thin section of the part. These are now widely treated on the gas hardening machine with so little distortion that they can be shrunk on to the flywheel without the slightest difficulty. Real heating economies are obviously obtained when the part is very massive and only a surface hardness is desired, since only the area to be hardened need be heated, thus avoiding the use of relatively large furnaces, necessary were the job to be treated in the ordinary way. Crankshafts provide an example of this. Only the pins and bearings need be hardened and this can quite easily be accomplished on the machine. To treat the same part in the usual way would involve a fairly large furnace maintained at

a considerable temperature while the bulk of the metal forming the shaft would be needlessly heated. Owing to the large mass of the part, the quenching would not likely be so effective as when the surface only is heated and subjected to a high-pressure douche under controlled conditions.

While the Shorter process may be classed as a special purpose heat treating machine, it can cover a wide range of work economically, and the accompanying photographs (Figs. 19 and 22) show only a few typical jobs.

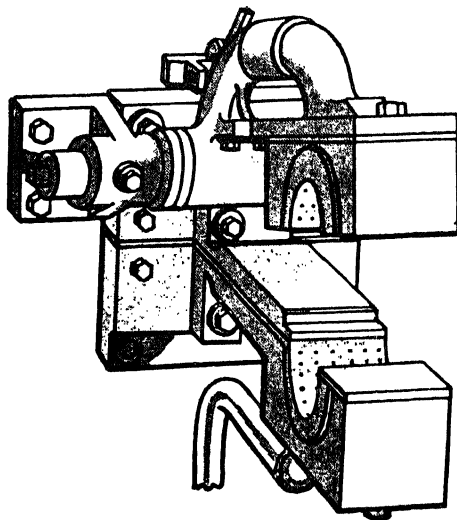


Fig. 24.—The Tocco process inductor block with its electrical and water hose connections. Automatic control applies the right amount of heat for the right time, following which the quenching is also entirely automatic

The Tocco Process

The remarks previously made with regard to hardening principles, types of steel, etc., when dealing with the gas hardening process, apply with equal force to the electrical process. Repetition of these general statements will thus be unnecessary here.

In principle the Tocco process is very simple, the heat being generated by induction. The electrical plant consists of a special motor-driven generator of 200 kW capacity. The

generator is a 90-pole machine which at its normal speed of 3000 r.p.m. gives current at a frequency of 2250 cycles. A special high-frequency transformer steps the generator voltage down to about 24 volts applied across the inductor ring. For hardening crankshafts, the inductor block is split so that it can fit over each pin or journal in turn without actually touching the work. The quenching jets are incorporated in the block to allow of the part being quenched at the appropriate moment. When the block is closed over the job and the power switched on a high frequency current of the order of 9000 amps. oscillates in the inductor. A similarly heavy current is, of course, induced on the work, and because of the "skin effect" of high-frequency current, by far the greater part of the energy is dissipated on the surface layer. So great is this heating effect that the surface of the work is usually over the critical point in about 5 seconds, while the core of the work is scarcely warm. By an automatic arrangement, the quench is turned on at the correct instant, usually taking about 10 seconds. Since special inductor blocks are usually required for each particular job, this machine is most economical on production, especially in treating complicated parts such as automobile crankshafts, for which purpose it has already proved itself to be a thoroughly satisfactory commercial proposition. It is also widely used for local hardening of axle shafts and work of a similar nature.

Since it is obvious that the whole success of the process depends on close control of temperature, which in this case depends on the time the power is on, a special feature of the machine is the automatic switching gear for controlling both the time the current is on and the timing of the quench. To set this controller, some experiment is necessary with the job so that the heating and quenching cycles may be properly adjusted, but once this information is obtained, a particular part may be treated at any time. Obviously this preliminary experimenting is not a disadvantage when setting-up the machine to deal with a large number of similar parts. The control gear for this process is shown in Fig. 23. The whole cycle of operations can be set out on the drums and repeated indefinitely. Fig. 24 shows the construction of the special inductor block, while Fig. 25 is a general view of the plant working.

General practice with this type of machine is to arrange a preheating furnace to bring the work to about 120° C. before treatment. After hardening a light temper at 150° C. is also

given in a separate furnace of orthodox construction. The object of the preliminary heat is to avoid shock to the parts when they are rapidly heated for hardening. The light temper after hardening, of course, is in line with ordinary practice and serves to toughen the hard skin. The usual layout for mass production methods is to have the preheating furnace, the hardening machine and the tempering furnace in a line, the work passing through each in turn on special conveyors (Fig. 25). In the case of crankshafts and other work where the sizes of pins and journals have to be held to close limits, the procedure is to harden after machining or grinding, say, 0.005 in. oversize. After treatment a final grinding operation brings the parts to the correct dimensions.



Fig. 25.—General view of production plant for surface hardening by the Tocco process

Since this machine is almost entirely automatic, it can be operated by relatively unskilled labour after the preliminary setting up. Provided the material being treated is uniform in composition and size, the results should be quite uniform also. At the present moment crankshafts, for example, are being commercially treated both here and in America on a production basis to give a hardness on the pins and bearings of the order of 700 Brinell. This might be a formidable programme to maintain in an ordinary heat treatment shop, having regard to the time taken, and the mass of the parts involved. A hardening machine, however, deals with this and similar work

in a much shorter time and much more economically from a machining point of view.

Hardening machines, whether gas or electrically operated, are attractive propositions for dealing with what would otherwise be an awkward job. It is in these cases that they naturally show to their best advantage. The heat-treater, however, should not lose sight of the possibility that ordinary furnace methods in some cases show a better financial balance sheet. Accordingly, these highly interesting methods should not be regarded as a heat treatment "cure all" but rather as a special tool. Viewed in this light their advantages (and they are many) will not be overestimated and impossible results expected of them.

CHAPTER V

Hardening Carbon and Alloy Steels

In previous chapters, a general outline of hardening and tempering, as well as the types of furnaces used, has been given, and now it is proposed to deal with particular types of steel such as are commonly met with in commercial practice. As has been shown already, casehardening is essentially a surface-hardening process and does not by any means meet



Fig. 26.—1.08 carbon steel
slowly cooled cementite net-
work and lamellar pearlite.

× 500

every engineering requirement. The never-ending quest for high strength associated with toughness has been largely responsible for the development of alloy steels which are capable of being heat-treated to withstand high stresses. Many thousands of tons of these steels are consumed annually, in the shape of forgings, by the automobile and aircraft industries.

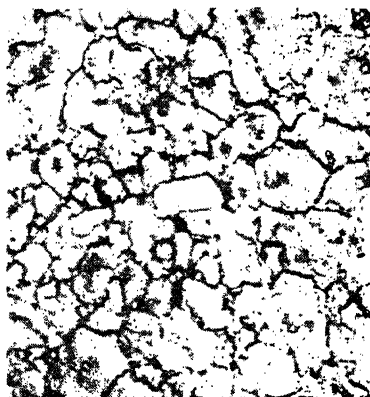
In the field of cutting alloys, of course, tools must be uniformly hard and the insistent demand for higher output has led to a great extension in the use of alloy tool steels. These

steels, however, have usually a well-defined sphere of application as have also the simpler and cheaper carbon tool steels. In general, the higher carbon specifications, especially when associated with alloys, because of their sensitiveness to heat treatment and their ability to acquire high hardness, may be regarded as tool steels and are often met with in applications where one or more of their superior properties are fully exploited.

Before going on to consider this class of steel in detail it may be well to consider the influence of each alloy on the heat



High-speed steel, 18:4:1 type, annealed 800° C., showing numerous carbide particles. X1200



High-speed steel, air hardened 1300° C. Complex carbide in an austenitic matrix. X 1200

Fig. 27

treatment and the physical properties. Naturally, these can only be stated in general terms here, but they give a useful guide to the properties which may be expected.

Carbon.—By forming a compound with the iron (Fe_3C) carbon acts as a hardener in the normally cooled steel. It also enters into solid solution with the austenite and tends to retard the change from austenite to pearlite. Hence, with increasing carbon the steel becomes increasingly "hardenable" (Fig. 26).

Nickel.—Forms solid solutions with both the ferrite and the austenite and lowers the transformation temperatures. It thus acts as a "toughener," yielding increased tensile strength without any special heat treatment. In normal forging grades

of steel (about 0.45% carbon), each percentage of nickel up to about 5% will give an increase in tensile strength of the order of 2 tons per sq. in. without heat treatment.

Chromium.—This alloy readily forms carbides in association with the iron and increases the hardness and depth of hardening. It also tends to produce a fine grain, thus increasing the strength and toughness. It has a pronounced retarding influence on the change of austenite to pearlite, and so hardens fully at relatively slow rates of cooling. The hardening temperature is raised by increasing chromium.

Tungsten.—This element is very similar to chromium, forming carbides and other complex compounds readily. It also raises the hardening temperature. Once the austenite solid solution is formed it tends to stabilise it at ordinary temperatures. It also exerts a powerful "obstructing" influence on the normal changes induced by tempering. Steels containing considerable percentages of this element resist tempering at temperatures which would speedily soften an ordinary carbon steel (Fig. 27).

Molybdenum.—Because of its effect in raising the critical ranges on heating, the effect of molybdenum is to raise the hardening temperature. It is also a powerful "obstructing" agent, like tungsten, and is about twice as effective. While it is not an exact substitute for tungsten in high-speed steels it enters into the composition of many, replacing part or all of the tungsten, because of its great similarity to that element.

Vanadium.—Vanadium forms carbides and is usually only present in minor percentages. It is an excellent grain refiner and in general tends to raise the hardening temperature. This can be safely done without detriment, since its fine grain tendencies prevent brittleness.

While the elements which have been enumerated singly above each exert their own peculiar influence in steel, it is but seldom that they are used alone. More often various combinations of these alloys are used, each particular alloy contributing its own peculiar properties to the complete steel. Many such alloys have become almost "standard" types, the best proportions of the elements having been found by experience, and these are most often found in practice. For example, simple nickel steels are usually found in 1%, 3% and 5% grades, nickel-chrome steels are similarly standardised, high-speed varieties fall into well-defined groups, and so on throughout

the whole range of alloy steels. This arrangement allows of considerable simplification from a manufacturing point of view as well as allowing some standardisation of heat treatment, and thus encourages cheaper and better steels. Consequently, in commercial heat treatment, the number of alloy compositions which are dealt with is reduced to a reasonable basis, and specifications outside the usual standards are seldom encountered except for very special reasons.

While the ordinary "mild" carbon steels can be normalised and refined in the grain by suitable heating and cooling, very little increase in hardness will result even from the most drastic quenching. As the carbon content is increased, the steel becomes progressively "hardenable." At about 0.60% carbon, quenching will produce a sufficiently hard material to be useful for some types of tools and, consequently, steel containing this amount of carbon and upwards are designated tool steels. There is, however, no hard and fast line of demarcation, and it should be remembered that steels containing less than this amount can still be hardened. For example, many forgings are made at about 0.35% carbon, and are regularly toughened for special purposes by quenching in oil. This mild quench, of course, does not fully harden the steel, but by cooling rapidly enough refines the grain and sorbitises the pearlite. The mass of the forging, of course, is a limiting factor in the practicability of such a treatment. In the tool steel class full hardening and tempering treatment can be given. Here, again, the mass of the part is important. As a general rule it can be said that for a given hardness the smaller the part the lower can be the carbon. As will be seen later, the very important influence of mass as it affects hardening can be largely compensated by alloy compositions. The table below gives suitable forging and hardening temperatures for the full range of carbon steels:

% C.		Forging temp. °C. (max.)		Hardening temp. °C.
0.25	...	1200	...	850 (in oil for toughening)
0.45	...	1200	...	830
0.75	...	1150	...	810
0.90	...	1125	...	800
1.00	...	1100	...	790
1.20	...	1050	...	780
1.30	...	1025	...	770
1.50	...	1000	...	770

The following table shows typical uses for these steels:

% C.	Used for
0.25	Structural steels, soft forgings, small castings.
0.45	Harder forgings, pins, levers, and other parts usually heat-treated for toughness.
0.75	Hammers, dies, mining drills, rivet setts, wedges.
0.90	Hand chisels, punches, small shear knives, drop-dies for cold work, saws.
1.00	Reamers, drifts, broaches, milling cutters, springs, cutting and trimming dies.
1.20	Woodworking tools, twist-drills, taps and dies, cutlery, general turning and planing.
1.30	Razors, drawing dies and other tools requiring extreme hardness. Chilled roll turning.
1.50	Special turning and planing tools.

The quenching of these steels for hardening requires consideration. If water is used there is an increasing risk of cracking and distortion as the carbon increases. As in all hardening practice, the shape of the job greatly influences the mode of hardening. Sudden changes in section, sharp angles, especially re-entrant ones, holes previously drilled, all have an effect on the final hardness attained. It will usually be found that parts surrounded by relatively large masses of material fail to harden as effectively as corners or thin sections. Unless these possibilities are studied in relation to the design and method of quenching a good deal of cracked and distorted work will result. Oil quenching is often adopted to give the required hardness directly, instead of quenching for the hardest possible structure and tempering to the required figure. While something can be said for the direct method in complicated designs which might fracture in water, the direct method must necessarily leave residual strains in the material. The tempering tends to relieve these strains and so avoids risk of sudden failure. Incidentally, the higher the tempering temperature that can be borne without losing the necessary hardness the more beneficial will be the result. In the softer forging grades of steel the forging itself tends to break down any coarse structure which may arise as a result of the high temperatures used, but the best practice is to normalise by heating to the hardening temperature and cooling off in still air. For larger forgings the air cooling may not be effective enough, and oil or even water quenching may be adopted. After quenching, however, rough forgings are always reheated to about 600° C. for an hour or so according to size. This treatment, being conducted under A_c1 , no structural change in the grain takes place beyond a tempering effect in which the hard-quenched structure is resolved into the tougher sorbitic type of structure. At the same time internal stress is greatly relieved and the



Fig. 28.—Well defined martensite showing characteristic “needle” structure. The coarseness of this structure indicates that the steel has been overheated in hardening

steel is placed in an excellent condition for machining. Such treatment is often given to relatively low-carbon alloy steel forgings prior to machining in preference to a prolonged anneal, being both faster and nearly as effective in reducing hardness.

In the tool steel range the effect of quenching is to produce the extremely hard and brittle martensite. The object of tempering is to break down this constituent into softer and tougher products. As has been explained already, martensite is a relatively unstable solid solution of carbide in alpha iron (Figs. 28 and 29), and the effect of heat, even at quite low temperatures, is to disturb this unstable condition. Recent research has shown that possibly two forms of martensite may exist. One form, produced by quenching tool steel right out, is hard and brittle, but the other form, equally as hard, is much tougher and is produced by tempering the hardened steel at as low a temperature as 150° C. Reheating the steel to higher temperatures brings about the progressive decomposition of the martensite, producing successively troostite, sorbite and, when the critical point is finally reached, pearlite. Hence, any degree of hard-

ness between the quenched steel and the normalised steel may be obtained by tempering at a suitable temperature. The tempering temperatures used in practice, however, are confined to a relatively narrow range, usually from 150° C. to about 300° C. The lower temperatures give the hardest results. Up to about 250° C. is satisfactory for such applications as turning tools, cutlery, cutting dies, drills and similar work where hardness is highly important. From 250° C. to about 300° C. covers such applications as chisels, saws, springs and so forth, where



Fig. 29.—Coarse acicular martensite due to overheating in hardening

toughness is at least as important as hardness. The effect of tempering on hardened carbon steel is very critical, a difference of even 5° C. making an appreciable difference on the properties. The practical effect of this statement is that the tempering process must of necessity be accurate. In modern hardening shops oilbaths thermostatically controlled are frequently used, or special electric furnaces heating the work by forced circulation of the air may be adopted. The oilbath is most useful for small runs of work, while the furnace, of course, is better adapted to larger parts or bigger amounts. The time of tempering need only be long enough to allow the heat to

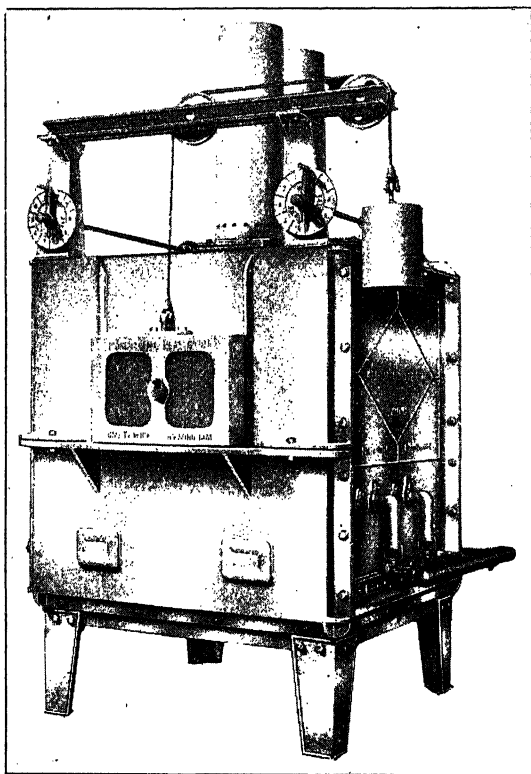


Fig. 30.—A town gas fired recuperative furnace designed for both intermittent and continuous operations. All heat treatment processes throughout the temperature range of 1200° C. can be handled

Incandescent Heat Co. Ltd

penetrate the job uniformly, and is commonly allowed to be about 1 hour per inch of section.

Some remarks on the heating of high-carbon steels, including alloy types, may not be out of place here. As a general rule, the higher the carbon content of the steel the more easily will it be harmed by bad treatment. In the hardening of these steels particular care must be taken to avoid too rapid heating. Where large quantities are being dealt with it is common practice to heat up the charge with the furnace, but in smaller

work some form of preheating furnace is often adopted. Warming up to a dull red heat slowly before bringing to the full hardening temperature is always safe practice. The atmosphere of the hardening furnace also requires attention. A furnace which decarburises the surface of the work makes necessary the provision of excessive grinding allowances to get rid of "mush," and consequently earlier remarks on controlled

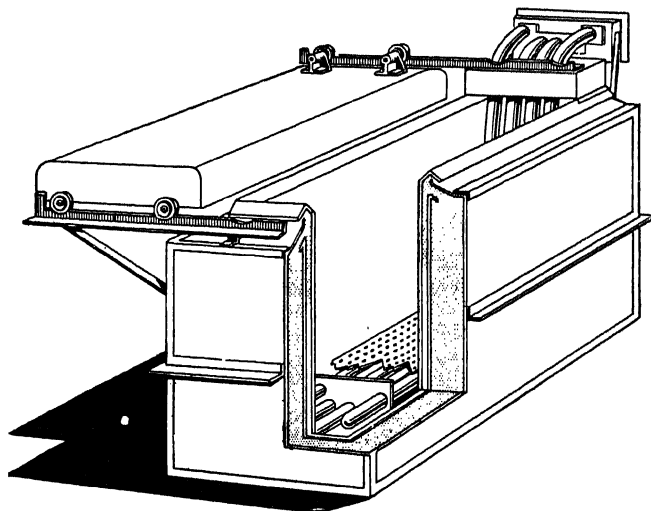


Fig. 31.—A large salt bath for tempering, etc.

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atmosphere furnaces should be carefully studied. The quenching of these steels also calls for some special precautions. The manner in which the parts are placed in the quenching bath controls to some extent the amount of distortion. Special work such as ring gears are likely to go oval or buckle, even with careful quenching, and special jigs are often used to prevent this. Care should be taken in designing such jigs, however, that they do not shield any considerable area of the work from the effect of the quench, otherwise soft spots will be developed and distortion will perhaps be worse than ever. Figs. 30 and 31 show suitable furnace equipment for handling the heat treatment of this class of steel. The gas-fired hardening furnace and salt bath (both thermostatically controlled) would be good practice in an up-to-date shop handling repetition work.

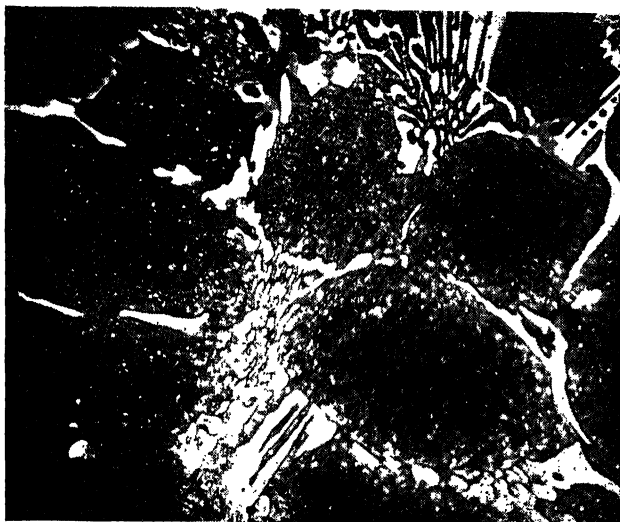


Fig. 32.—Typical cast structure of high-speed steel. The white constituents are agglomerates of carbide-tungstide complexes. After forging these are broken down and more evenly distributed throughout the mass. On heating to the hardening temperature, these smaller particles are more readily taken into solid solution and retained on rapid cooling. The steel as it stands would not harden effectively and would be brittle

Alloy Steels

Since the treatment of the alloy steels of this class is not essentially different from the plain carbon types, except that as a rule milder quenches are capable of developing full hardness, it is not proposed to deal with them in great detail. As has been noted already, the alloying elements modify to some extent the hardening temperature. The table below gives some figures by which the raising or lowering of A_c , may be calculated for any composition, knowing the figure for the carbon. The figures given are the number of degrees the critical range is raised or lowered for each 1% of added element. The temperature thus calculated has been found to check very closely with makers' recommendations.

Alloy Element	°C. raise or lower
Nickel ...	11° lower
Chromium	17° raise
Molybdenum	33° raise (in carbon-molybdenum steel) 83° raise (in chrome-molybdenum steel) 56° raise (in nickel-molybdenum steel) 86° raise (in nickel-chrome-molybdenum steel)
Manganese	30° lower

From the above figures a very good guide to the proper heating temperature may be calculated, provided the analysis of the steel is known.

While it would be impossible to give full details of every type of alloy steel in use to-day, the following list covers those most often encountered in the hardening shop. Of course there are slight variations in analysis, particularly in specifications which allow elements such as molybdenum, vanadium or tungsten to be present at the maker's discretion. Usually, if a standard specification is issued, a standard heat treatment is also given designed to cover all expected manufacturing variations. Consequently, hardening temperatures as given by the makers often appear higher than would seem necessary, but, within limits, little harm is done to the steel because of this.

Steel	C	Ni	Cr	Mo	Used for
S76	0.40	1.00	—	—	45-ton steel for forgings.
3%Ni	0.30	3.10	—	—	50-ton for forgings.
S69	0.40	3.50	0.10	—	55-ton steel for forging.
S11	0.30	3.50	0.80	—	55-ton Ni-Cr steel for forging.
S65	0.25	3.00	1.25	0.25	65-ton steel for forging.
S28	0.30	3.90	1.25	0.25	100-ton air hardening steel.
—	0.90	—	0.50	0.50 1.10 W Mn	Non-deforming die steel.
—	0.90	—	0.50	—	Chisel, saws and files.
—	1.0	—	1.75	—	Bearing steel.

Some general points in the heat treatment of these steels are worth remembering. If they are in the form of rough forgings to be machined subsequently, a preliminary heat treatment should be given to soften them sufficiently for machining. In most cases a full anneal is too slow for production reasons, and the general procedure is to use a tempering method to obtain the required softness. In the case of the lower carbon steels the procedure would be to normalise the parts by heating to a temperature over the critical and simply air cooling. When they have reached a temperature of about 300° C. they may be reheated to about 600° C. (well *under* the critical range) and again air cooled right out. This procedure may be varied in the case of the higher carbon

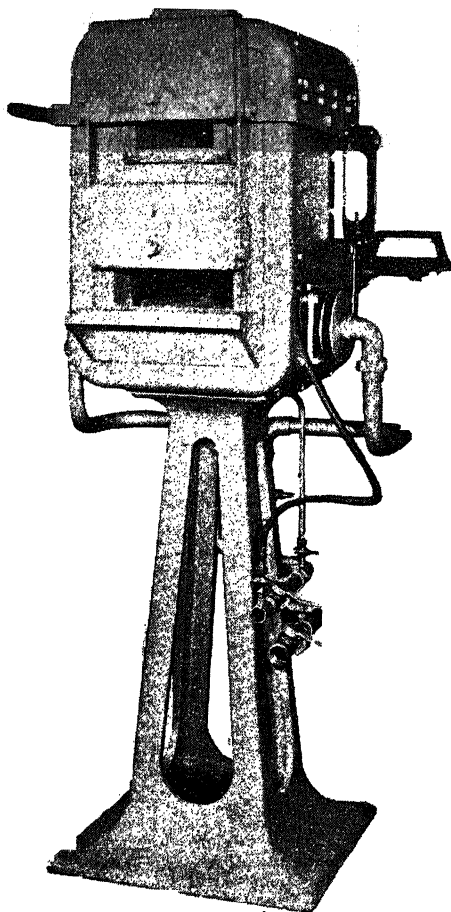


Fig. 33.—G.L.C. high-speed steel tool-hardening furnace, suitable for rapid attainment of working temperatures and economic operation at a temperature of 1350° C. in the hardening chamber; the upper or preheating chamber is maintained at approximately 800° C. by waste heat from the outgoing gases

higher alloy types by furnace cooling from the first heat down to about 200° C. and tempering as before. In this way it is

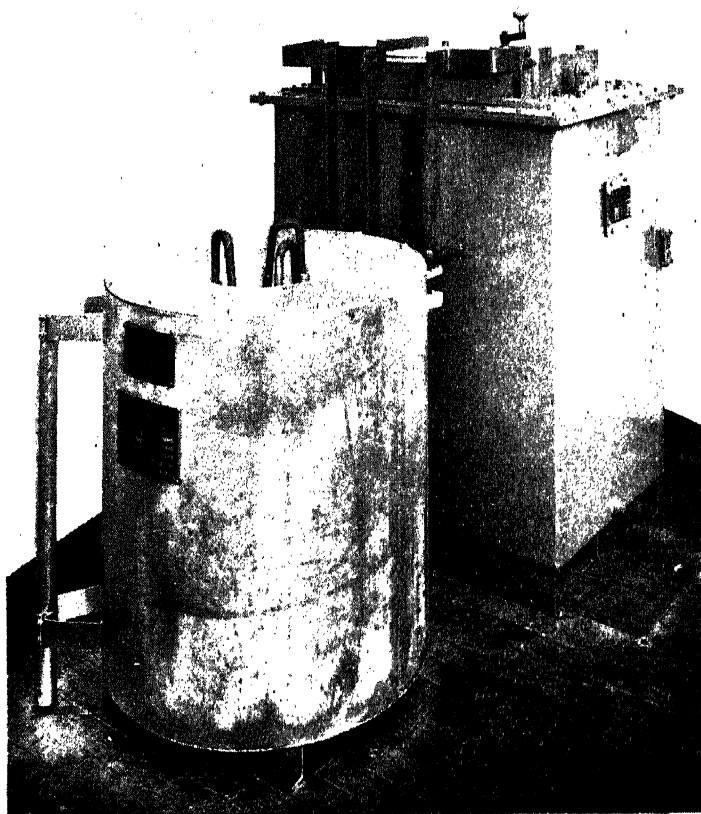


Fig. 34.—High-temperature tool-hardening salt bath electric furnace

The General Electric Co. Ltd.

always possible to place the steel in a reasonably soft condition for machining. The only precautions to be observed are to see that the initial temperature is not far in excess of the upper critical point and that the soaking time at this temperature is adequate for the work.

In treating these steels for machining it is usually desirable to normalise the rough forging or bar before machining by

some such treatment as outlined above, since a good deal of distortion arises when machining untreated work due to the release of cooling strains. This is a very important point in precision machining and should never be overlooked in such cases.

High-speed Steels

Modern high-speed steels stand in a class apart from other cutting steels. The carbon content is not usually very high, but tungsten and chromium are always present in considerable quantities. In addition, molybdenum, vanadium and cobalt may be present. This complicated alloy, principally because of the tungsten (and/or the molybdenum) requires an exceedingly high temperature to harden, *i.e.*, for a homogeneous solid solution to form; and conversely, once this solution is formed it is unusually stable. Tempering temperatures are consequently high. The hardening temperature for these steels is in the neighbourhood of 1300° C. and tempering temperatures of 580° C. are common.

Before going on to consider the high-speed steels proper, some attention may be given to the tungsten steels generally. Tungsten in steels in amounts under 1% does not greatly influence the hardening temperatures, since this amount raises the critical points by only about 5°. In tool steels (*i.e.*, high-carbon steels) its most obvious effect is as a grain refiner, producing a dense, fine grain steel. It is probable that this has much to do with the superior cutting properties developed. If tungsten is present alone, the steel will still water harden without cracking, although the presence of chromium as well makes it more sensitive in this respect. Tungsten-chrome alloys are, therefore, predominantly oil hardening. The chromium, however, decidedly increases the "hardenability" and depth of hardness attained, and vanadium also helps to attain this end. Consequently, tool specifications commonly include chromium and often vanadium.

Classification

The classification of these steels is difficult, since many manufacturers have developed special purpose compositions in this range, but they may be divided into low-tungsten tool steel, fast-finishing steel and true high-speed steel. Steels containing carbon from 0.5% upwards, with up to 2.5% tungsten and perhaps 0.5% chromium and 0.25% vanadium, find wide

application in the manufacture of small tools of all kinds, such as chasers, taps, reamers, drills and hack-saw blades. Steels containing 2.5% to about 7% tungsten form the "fast-finishing" class, and are usually over 1% carbon content with about 0.5% chromium. These find application in light, fast-finishing cuts and are principally used for lathe and planer tools for producing a fine surface. The true high-speed steels are usually of medium carbon composition associated with high percentages of tungsten, chromium and vanadium, and their properties are well enough known among engineers. The table shows some typical compositions.

C	W	Cr	V	
1.0	1.2	0.3	—	Low tungsten tool steel.
1.1	2.0	0.5	0.25	Used for broaches, reamers, etc.
1.2	5.0	1.0	0.15	"Hard" fast finishing.
1.1	4.0	0.4	—	Typical fast finishing.
1.2	7.0	0.4	—	Special fast finishing.
0.6	18.0	4.0	1.0	High-speed steel.
0.6	14.0	4.0	2.0	High-speed steel.
0.6	15.0	3.5	0.5	High-speed steel.
0.7	20.0	4.5	1.5	Super high-speed steel.
0.7	20.0	5.0	1.5	0.5Mo 12Co Super high-speed steel.

It will thus be seen that the tungsten alloy steels cover a wide range of compositions, although the heat treatment can be readily arranged to suit any particular type. The hardening temperature for the low tungsten type is usually moderate and frequently occurs about 800° C. Slow heating and tempering at about 200° C. are recommended. In the absence of chromium or if the chromium is below 0.5% water, quenching may be employed. The advantage of low chromium in the composition lies in the remarkable non-deforming properties of the straight tungsten steel.

The fast-finishing class approach nearer the true high-speed type and consequently require a higher hardening temperature about 900° C. or over.

The high-speed types, of course, require temperatures in the region of 1300° C. for hardening.

Rate of cooling of the higher tungsten types is important also. The fast-finishing types should be oil quenched, since the tungsten greatly retards the gamma to alpha change and the high-speed types are usually air-hardening for the same reason. Consequently, good commercial practice is to make the most drastic quench for these tools in an oil bath, and in the case of high-speed types the oil is often warmed slightly or an air blast is used. The heating technique for the lower

tungsten types, however, is not radically different from the usual practice with high-carbon tool steels.

With high-speed compositions, a different practice is necessary. These steels are relatively poor conductors of heat, and ample preheating is absolutely necessary. The usual commercial practice is to heat slowly to about 800° C. and then rapidly to the full hardening temperature. At this temperature the carbides of tungsten and other inter-metallic

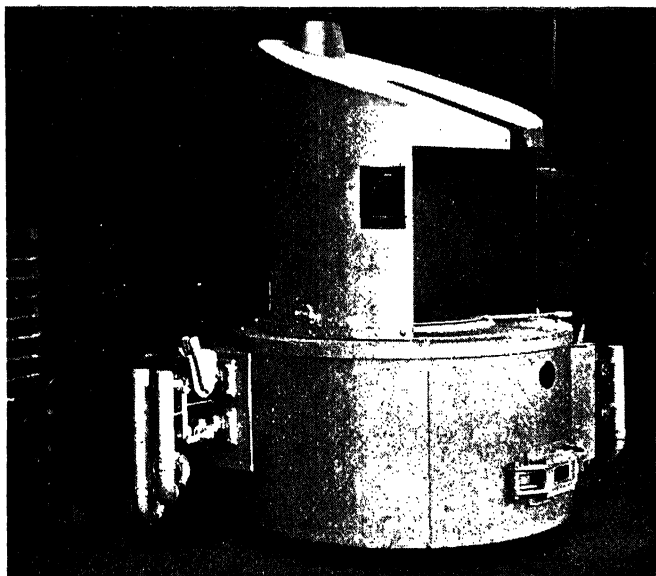


Fig. 35.—Gas-fired furnace, with a pot 24 in. in diameter and 21 in. deep. No preheater is shown, but one can be attached quite simply

Imperial Chemical Industries Ltd.

complexes are taken into solid solution and are retained on moderately rapid cooling, such as oil quenching or cooling in air. This solid solution is very hard, and tools in this condition may be put to work successfully. A further rise in hardness, however, is obtained by tempering (the so-called "secondary hardness"), while a certain amount of hardening strain is removed by the re-heating. The temperature required to develop secondary hardness is about 580° C. for ordinary compositions, and this treatment should never be omitted for any but the roughest work. Tools of "super" composi-

tion, especially those containing cobalt, actually depend largely on the tempering treatment to bring out their superior qualities. Comparison of Fig. 32 with Fig. 27 will show the profound influence of heat and forging on high-speed steel. In particular, the remarkable effect of the high temperature hardening heat on the material should be noted. The breakdown of the cast structure (Fig. 32), on forging, to the laminated form (Fig. 27) should also be observed.

Method of Heating

The method of heating these steels calls for some comment. The preheating furnace should preferably be of the muffle type, but need not have any special protection for the atmosphere, since high-speed steel scales but little at low temperatures. The high heating chamber, however, should have some such protection since scaling at this temperature may lead to serious decarburisation. Sometimes salt baths, containing fused inactive salts heated by passing a low-voltage current through the mass, are used for the high heat, the salt being relied on to protect the surface. Such protected heating methods are desirable for treating form tools, milling cutters and similar parts, thus avoiding excessive grinding allowances. The tempering treatment may be carried out without special precautions as to atmosphere and a small electric muffle type of furnace is often used for this purpose. In the production of large numbers of parts, thermostatically controlled pre-heating and hardening furnaces are employed and a rigidly controlled time and temperature programme is adopted. The time at the high temperature influences the grain size, and hence the toughness of the tool to a marked degree, and must be rigidly controlled for accurate work. This time should be no longer than that necessary to absorb into solid solution all the free carbide, etc. If prolonged beyond this point it will lead to large grain growth. It need hardly be stressed that some form of pyrometer equipment is desirable for control purposes, even if no other control gear is available. Suitable furnace equipment for treating these steels is shown in Figs. 33, 34 and 35.

Softening high-speed steel for machining raises special problems. It is not possible to anneal this material in the usual way, since it is so intensely self-hardening, and the best procedure is to temper the fully-hardened steel at about 700° C. The full anneal is carried out by heating to 900° C., raising the heat very gradually, soaking at that temperature and

furnace cooling. By this prolonged cooling, the steel is made as soft as possible, but the process is necessarily a long one.

The technique adopted in tempering after hardening is on the following lines. The tool is heated up to the high hardening temperature, quenched either in oil or air blast, and placed in the tempering furnace before it has become quite cold. If the tool is allowed to cool right out, there is a grave risk of cracking occurring later.

Finishing these tools by grinding sometimes gives rise to cracking and checking, even if the correct grade of wheel and speed are used. Such cracking can usually be traced to decarburising of the surface and need not occur when the hardening has been properly carried out. Another source of cracking arises from water particles carried in the cooling air blast. A good trap in the compressed air line will cure this complaint.

CHAPTER VI

Stainless and Rustless Steels

Perhaps there is no branch of metallurgy which has shown such striking advances than that dealing with the stainless and rustless steels. From the relatively simple alloys of only a few years ago, with their limited application, we have to-day a number of highly-specialised steels, many of them of great engineering importance. Such parts as exhaust valves for internal-combustion engines, various details to withstand high temperature, high pressure superheated steam, and vessels for handling chemicals, foods and corrosive material are now regularly made with one or other of the many stainless and rustless steels available. While it would be outside the present scope to dwell in detail on the alloys available and all their applications, they can be roughly classified readily, and their scope outlined so that an intelligent appreciation of their treatment will be obtained.

All these steels contain chromium in considerable percentages, while some contain nickel also. The early steels tended to run high in carbon due to difficulties in manufacture, but modern high chrome steels can now be made with lower carbon content, principally because of improvements in melting technique during manufacture. Even so, it should be remembered that low carbon steels of this class are still more expensive to manufacture than the harder grades, and although the disparity in cost is not now so great as before, it is still wise when drawing up specifications not to insist on softer grades than are necessary.

The corrosion-resisting steels may be classed under five main groups, and while there are other types outside this classification, they are not of sufficient general importance to be considered here. These types are as follows:

1. Soft engineering;
2. Cutlery type;
3. Valve type (heat resisting);
4. Soft malleable;
5. Austenitic ("18:8").

As the carbon content increases the chromium content can be slightly lowered in the first four types, while in the fifth type the carbon is always under 0.2%, since extreme malleability is an outstanding characteristic of this material. Typical analyses of these steels are given below.

TABLE I

No.	C.	Mn.	Ni.	Cr.	Other elements	
1 ...	0.13 ...	0.55 ...	0.5 ...	14.0		
2 ...	0.35 ...	0.35 ...	— ...	14.3		
3 ...	0.55 ...	0.50 ...	— ...	9.0	Si 3.0	
4 ...	0.10 ...	0.20 ...	— ...	15.0	Si 0.5 max.	
5 ...	0.15 ...	0.25 ...	9.5 ...	19.0	Ti, Mo, Cb, may be present	

On studying the table, it will be evident that the first four types are essentially high chromium steels with varying amounts of carbon. Because of this high percentage of chromium, these steels are all more or less self-hardening, that is, they tend to become martensitic on air cooling alone. Since chromium raises the critical points considerably, the hardening temperatures, as would be expected, are unusually high. Consequently the heat treatment resembles in many respects that of high speed steel. Forging and working temperatures are also high. As a rule, any attempt to work this material below 900° C. sets up such stresses that it cracks either during the working operation or subsequently. While this high rigidity at high temperature is somewhat embarrassing to the forger, it is a valuable property to the engineer. Its heat resistance and high strength at temperatures where other steels would be plastic, finds many applications for highly-heated and stressed components. As was mentioned above, the self-hardening tendency of the chromium steels usually leaves them in an unmachineable condition after forging. In order to anneal, it would be necessary to cool very slowly indeed from the forging temperature. For economic reasons, this procedure is not often followed. Fortunately, the steel can be tempered to a machineable hardness in a much shorter time, and the full annealing treatment is only adopted if there is good reason, such as for purposes of stress relief. Tempering the hardened material at 650° for about one hour per inch of section should result in a Brinell hardness of 300 or less, and this can be machined satisfactorily. Incidentally, this slightly harder steel often gives a superior finish at fast machining speeds than the fully annealed steel.

In order to develop corrosion resisting properties to the full, it is essential that the steel should be in the fully-hardened

condition. Thin or intricate sections can usually be satisfactorily hardened in the air blast or in oil without much risk of distortion. Oil quenching or even water quenching can be adopted for medium sections. Oil is, however, preferable for complicated shapes, since water introduces a cracking risk. The more severe the quench, the more the necessity arises for subsequent tempering to relieve the considerable stresses set up, and consequently it is usual to specify a light temper at 150° C. to 200° C. after quenching.

The furnace technique for hardening follows very closely that for high speed steel, although the temperatures involved are not quite so high. Like high speed steel, this steel has a low heat capacity, absorbing heat very slowly, and consequently a thorough pre-heat at about 600° C. is highly desirable. A stock furnace maintained at this low heat is often used for preheating, the steel being transferred to the higher temperature furnace as required. In this way the high temperature furnace need not be of large capacity, and continuous working can be arranged economically. The final hardness obtained depends also on the initial temperature to which the steel is heated, and consequently some latitude is allowed in the temperature of the high heat furnace. The usual temperature maintained is in the region 950° to 1000° C. The table below gives the hardening particulars of the four typical steels:

TABLE II

No.	Hardening Temp. °C.				Full anneal from			Forging Range
1	970-1000	...	...	...	850	...	...	870-1050
2	960-1040	...	...	...	880	...	...	930-1100
3	1040	...	...	...	860	...	...	950-1050
4	980	...	...	...	not necessary	...	...	about 1050

Inasmuch as steel No. 4 is of the "dead soft" type, it is not usually necessary to anneal for softening. Although a hardening temperature is mentioned for this steel, the tendency for it to harden is very slight, about 300 Brinell being the maximum. It thus becomes a very useful material for conditions where machining is necessary after quenching. The valve type (No. 3) is also worthy of notice. This is a high carbon type in which some of the chromium has been replaced by silicon. The silicon considerably reduces the air-hardening effect of the chromium. A self-hardening valve on running in an engine will, in parts, reach temperatures in excess of the critical. On cooling, the transformation will occur at about 300° C. with considerable expansion of the steel. The

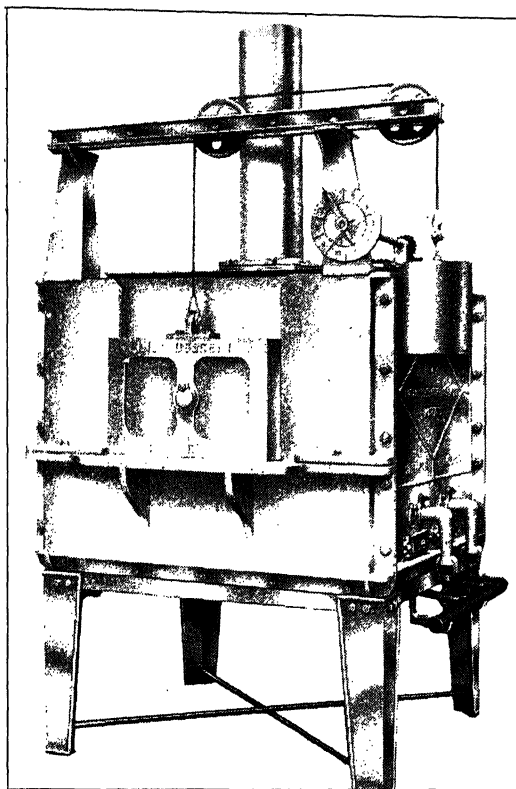


Fig. 36.—A gas-fired furnace for any kind of heat treatment within a working range of 1100° C. and suitable for treating stainless steels

Incandescent Heat Company Limited

function of the silicon is to cause this transformation to occur at a higher temperature, thus obviating the risk of fracture. Nevertheless, this steel can be hardened by quenching in oil from a fairly high temperature, as shown in the table. Tempering of these steels, as already stated, lowers the resistance to corrosion slightly, but in this particular case this is largely offset by the presence of the silicon.

The cutlery type of straight chrome steel is often adopted for applications where toughness as well as corrosion resistance is called for. To increase the ductility somewhat, higher

tempering temperatures are adopted, but a peculiar type of corrosion is likely to occur when tempering in the range 520° to 580° C. This range and its neighbourhood should therefore be avoided when tempering.

The corrosion of iron and steel is largely an electrolytic phenomenon, and for highest resistance the steel should be free from seams, cracks and other imperfections where slight potential differences may exist. In the case of stainless steels, even a coating of scale will cause rusting in a steel which is otherwise good and in the proper condition, and consequently, after hardening and tempering, they should be pickled. Commercial solutions for this purpose are now readily obtainable and consist chiefly of some strong acid with accelerating salts added. In many cases sandblasting or grinding is all that is necessary.

The furnaces for treating this material need not have very elaborate atmosphere control, some form of muffle being satisfactory. These steels resist scaling to a remarkable degree, scarcely any scale being formed below 800° C. As a result, the material may be handled much more freely than lower alloy steel, but is, of course, still subject to grain growth. Exposure to the high temperature should not, therefore, be excessive (Fig. 36).

Austenitic Stainless Steel

The remaining type of steel to be considered (No. 5, Table I) is the widely used 18:8 type. Here we have a material which has no thermal transformation, i.e., it remains austenitic down to ordinary temperatures. The low carbon varieties are characterised by their high ductility and find their greatest application in presswork, especially deep drawing. As will be seen, they contain considerable proportions of nickel as well as high chromium. The nickel stabilises the austenite, and accordingly rapid cooling from a high temperature softens the alloy by retaining the solid solution to atmospheric temperature. The steel, however, rapidly hardens by cold working, due to crystalline distortion. In this condition it is most susceptible to corrosion.

In view of its peculiar physical condition, being a perfectly stable and homogenous solid solution, it is not possible to treat this steel by ordinary methods. Because of its unusual ductility it can be forged readily at temperatures slightly over 950° C. Any working below this temperature tends to distort

the crystalline structure and thus hardens the material. Such severe treatment as cold rolling or drawing will confer the maximum work hardness on the steel, but it is seldom that the Brinell hardness exceeds 350 even after this treatment. Since a distorted structure is rather more susceptible to corrosion than a normal crystalline arrangement, the aim of heat treatment on this material is to obliterate the effect of cold working. By raising the temperature of the steel to about 950° C., much of the stress is relieved, the distorted structure is recrystallised, and the steel is once more placed in its best condition. Quick air cooling or even quenching in water will not produce any further stress since the absence of any critical transformation, and the consequent absence of abrupt changes in thermal contraction precludes the possibility of shock or rupture. It is quite in order, then, to oil-quench even large work from 950° to 1000° C. The necessity for quenching this steel might be questioned on theoretical grounds, since any carbides that might be formed with the chromium must be small in quantity. Normally, these carbides are in complete solution and it is to prevent their precipitation on cooling that quenching is adopted. Any trace of carbide around the grain boundaries is fatal to the stainless properties, and it is known that in the region of 900° C. on cooling these steels do precipitate carbide. Quenching suppresses this undesirable reaction.

In this connection it is interesting to note that the application of welding to large vessels of this material brought this "carbide precipitation" peculiarity to light. Welded joints showed corrosion after a time, not on the weld itself, but at a distance from it on areas which must have reached 900° C. during welding. This only occurred on work which, because of its size, could not be readily heat treated, and any welded work which was heat treated was found to be quite immune to this "weld decay." Further research found that the elements titanium, molybdenum and some others in small quantities helped greatly in suppressing the trouble. Steel sheet or sections intended for welding now carry small percentages of some of these special elements, while the carbon content is always kept as low as possible. Welding rods also, of course, must contain the special element in order that the weld itself will be free from corrosion.

In spite of the benefits of these special elements, it is always best, from a corrosion resisting point of view, to heat treat this material whenever possible, after working or welding. In

making small articles which can be readily heat treated, there is no need to specify the higher alloy type. The heat treatment is not very elaborate and considerable economies can often be secured by adopting a simple alloy and heat treating rather than omitting the heat treatment and using the more highly alloyed material.

A suitable heat-treating programme for this class of material is not difficult to draw up. A good furnace, which may have a conditioned atmosphere to preserve the bright surface, heated to about 1000° C., and suitable quenching equipment is all that is required. The parts to be treated are then simply heated up to this temperature, held for a suitable time to allow the heat to penetrate, and immediately quenched. After this treatment, the steel will be in its softest condition, about 130 Brinell, and will show its highest resistance to corrosion.

CHAPTER VII

Non-ferrous Alloys

A great number of alloys apart from steel have been developed in recent years which require at least equal care in treatment to bring out their best qualities. Of this class, those most in the public eye at the moment are, of course, the light alloys so widely used in aeroplane construction. These high-duty light alloys owe many of their valuable properties to their sensitiveness to heat treatment. Indeed, to be economically worth while it is imperative that they should be properly heat-treated, since in the untreated condition they are little better than cheaper materials.

Most of the simpler kinds of non-ferrous metals and alloys harden appreciably on cold working, and a common expedient adopted to remove the brittleness and lack of ductility thus caused is to anneal the metal. For example, the well-known "cartridge brass," one of the copper-zinc alloys, is normally ductile and can be drawn cold to a remarkable degree. Metallurgically, this alloy, containing 30% zinc, consists of a simple solid solution of zinc in copper ("alpha" solid solution). Accordingly, the constitution of the alloy is a homogeneous crystalline material very like a pure metal. Since this solid solution is preserved from the solidification of the alloy down to atmospheric temperature, obviously no heat treatment can induce a change of phase with attendant recrystallisation. Heating this alloy to a fairly high temperature can, however, release the internal strain considerably and can overcome crystalline distortion by inducing grain growth. In general, annealing cold worked brass in a temperature range 600° C. to 650° C. will both remove the effect of cold working and place the material in the softest condition.

Annealing of Brass

The annealing of brass is often carried out in a controlled atmosphere furnace so that the bright surface is not damaged and most usually gas or electric muffle furnaces are used. The

time at the annealing temperature to which the work is subjected is the most important feature of the heat treatment. Prolonged annealing is both unnecessary and harmful, since excessive grain growth is thereby produced. Such a structure is weak mechanically, while as a secondary effect (sometimes important) the original smooth surface is spoiled. Annealing temperatures much in excess of the figures quoted are also harmful, especially if an oxidising atmosphere is at the same time maintained in the furnace. In this case there is risk that the brass will be "burnt," that is, so badly oxidised as to be brittle and useless (Fig. 37).

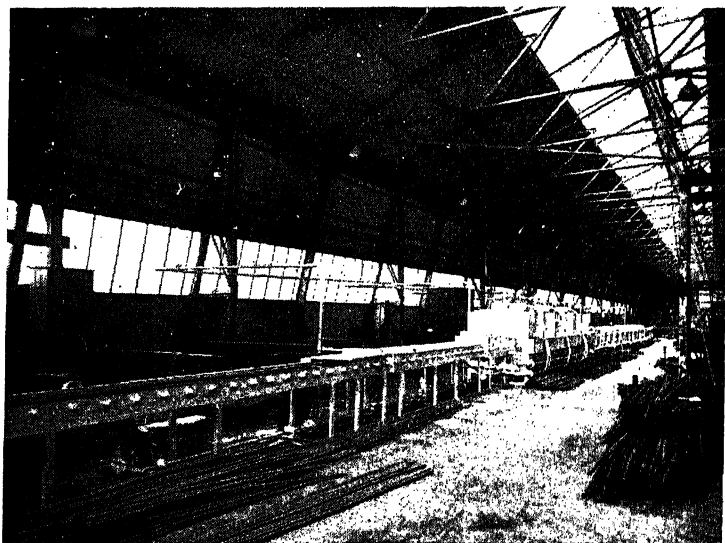


Fig. 37.—G.E.C. continuous bright annealing furnace at a large modern tube works

When the proportion of zinc is raised to about 40%, the alloy becomes duplex in structure, consisting of relatively soft crystals of the "alpha" phase mixed with a new constituent which is harder—the "beta" phase. The previous remarks on heat treatment of "alpha" brass apply to this type also, with the further proviso that as in this case we are dealing with a duplex alloy and in annealing for maximum ductility very slow cooling is essential. Rapid cooling of these brasses tends to retain the beta crystals which can only be transformed into the

more ductile alpha form by slow cooling after annealing. Consequently, as the zinc content of the brass rises towards about 40%, slow cooling becomes more essential to preserve cold ductility, and any quenching or other rapid cooling simply defeats the object of annealing. The 60:40 alloys on the other hand are always worked hot since they are much more plastic at high temperatures than cold. For this reason they enter largely into the composition of extruded sections, hot rolled material and forgings. Any further heat treatment is only given with a view to removing strain or distortion.

The introduction of other elements into brass, such as nickel and aluminium, gives rise to alloys which harden on heat treatment—the so-called “temper hardening” brasses. A typical composition is 6% nickel, $1\frac{1}{2}\%$ aluminium, $20\frac{1}{2}\%$ zinc and the balance copper. This particular alloy is *softened* by quenching from 850° C. in water. If cold worked and then submitted to a “tempering” treatment at 500° C., the hardness very greatly increases. Tensile strengths in the neighbourhood of 48 tons per sq. in. with an elongation of 11% can be obtained in this alloy in the fully heat-treated condition. The increase in hardness appears to be due to the precipitation of harder material from solid solution on heating to the low temperature. As will be seen later, this phenomenon is fairly general among heat-treatable non-ferrous alloys, particularly light alloys containing aluminium.

Turning now to the light alloys we find that as a class they are eminently heat-treatable, and in fact a very large number of such alloys have been patented and are in regular use in industry. This class is principally made up of the alloys of aluminium with such elements as copper, magnesium, silicon and nickel, separately or in combination. Another group of the light alloys are those of magnesium with small percentages of other elements. A great number of these alloys can be heat-treated to give very good physical properties considering the relatively poor mechanical properties of pure aluminium itself, and it is because of this that they find so many applications in aircraft construction in highly stressed components where lightness is all-important.

As has been demonstrated already, the ability of any alloy to alter its properties in response to heat treatment is intimately bound up with the formation of solid solutions and precipitation of components from such solutions. This idea,

while not by any means expressing the full story, will convey in a simple manner the meaning behind the various steps in the heat treatment of these alloys. It will be found that this is usually divided into two parts, which in the light of what has been said will be almost self explanatory. The two stages are (a) the solution treatment and (b) the precipitation treatment. The first step, it will be seen, consists of heating the alloy to such a temperature as will ensure that the desired solid solution will be formed. Once formed it is retained by quenching, and a subsequent heating to a lower temperature or even, in some cases, standing at ordinary temperature for long periods, allows the solution to precipitate a hardening component in an ultra-fine state. The fineness of the hardening precipitate would appear to have much to do with the high strength of the alloy.

The question now arises as to what alloys are necessary to form a metal having the peculiar physical properties outlined above. Investigation has shown that the solid solution is one containing an intermetallic compound or compounds. It is thus not a simple solution of one metal in another. As a rule, such compounds of one metal with another are hard and brittle, but when taken into solution and re-precipitated in an ultra-fine state, their very hardness adds greatly to the strength of the alloy. The nature of these compounds is analogous to a chemical compound, physically. It is a new material having properties peculiar to itself. It has been found that copper combines with aluminium in this way to form the compound CuAl_2 , while magnesium and silicon combine to form the compound Mg_2Si . Consequently an aluminium alloy containing these elements singly or together will necessarily be heat-treatable. A very large number of alloys fall into this class and the heat treatment will be found to vary only in detail among the various members. The procedure in general is to heat the alloys to about 500°C . and quench in water or oil according to the alloy. The hardening treatment in some cases is to allow the quenched alloy to "age" over a period naturally. In other types the "ageing" is accelerated by heating, sometimes by simply boiling in water or heating in hot oil up to about a maximum of 200°C . for a more or less prolonged period. These temperatures and times influence the final properties of the material, but generally the limits of control of such properties as hardness, ductility and tensile

strength can be readily determined and a suitable programme drawn up.

So much then for general principles. We shall now proceed to consider the heat treatment of aluminium and its alloys in some detail. A very large proportion of the aluminium alloy material used for fabrication is in the form of sheet, tube or sections. Usually, in assembling, a certain amount of cold working is performed on the metal as a result of which it often hardens and becomes brittle. Again, in deep drawing and similar operations only a certain amount of working can be done before annealing becomes necessary to avoid rupture. It is a peculiarity of these alloys that annealing can be carried

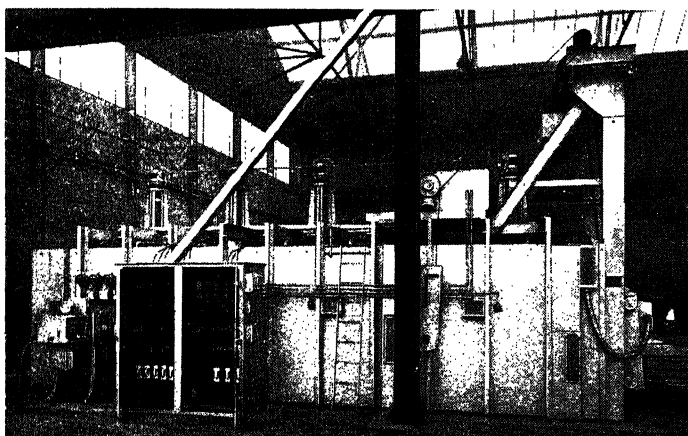


Fig. 38.—A 330-kW rectangular type G.E.C. electric annealing furnace with forced-air circulation

out at relatively low temperatures. As a general rule it has been found that annealing at high temperatures for a prolonged time gives rise to considerable grain growth and consequent weakness. It is safe practice in view of this danger, therefore, to limit the annealing temperature to 400° C. maximum. The time during which the part is exposed to this heat should be as little as possible; indeed, only sufficient to allow the heat to penetrate thoroughly.

Among the most interesting developments in the field of heat-treatable light alloys are the series of alloys developed by Rolls Royce Limited, which go under the general name of "Hiduminium R.R. Alloys." These all contain copper, nickel

and iron as well as magnesium and silicon, and a distinctive feature of the series is the presence of small, but important, additions of titanium. The titanium, by refining the grain, contributes substantially to the high physical properties which can be developed. Below will be found tabulated the composition and physical properties of two very well known members of this series, which are widely used for forgings as well as a heat-treatable casting alloy used for sand or die-castings required for high duty.

Name	Cu	Ni	Mg	Fe	Si	Ti
R.R.53	2.0	1.2	1.6	1.3	1.5	0.10
R.R.56	2.0	1.2	1.0	1.3	0.5	0.10
R.R.59	2.5	1.2	1.6	1.2	0.5	0.10

Name	Max. Stress	Elong.	Solution Treatment	Precipitation Treatment
R.R.53 ...	20 tons min.	—	Sand cast: 2 hours at 525° C. Die-cast: 4 hours at 510°-535° C. water quench (water at 70° C.)	10 to 20 hours at 165°-175° C. Cold water quench
R.R.56 ...	27 tons min.	10%	2 hours at 525°-535° C. Quench in water, 70°-100° C.	10 to 20 hours at 165°-175° C. Cold water quench
R.R.59 ...	25 tons min.	5%		

There are, of course, a number of other alloys which are susceptible to similar heat treatment. For example, Duralumin is a widely used material in the sheet form, and in the heat-treated condition gives a minimum tensile of 25 tons per sq. in. This alloy, which contains copper, manganese and magnesium, is solution-treated at 495° C., oil quenched, and aged spontaneously at room temperature over a period of about four days. The precipitation can be hastened by heating as in the other alloys but this reduces the maximum properties somewhat.

From what has already been said regarding these alloys, it will have been gathered that the temperature of heat treatment is all-important if the best properties are to be brought out. In dealing with light alloys, perhaps even more so than with any other material, accuracy of temperature is important. Furnaces should be chosen for this work which at the worst do not vary by more than $\pm 5^\circ$ C. from their nominal temperature. Modern gas or electric muffle furnaces are very suitable and are often used for this purpose. In view of the low temperatures involved, much of the heating of sheet and other wrought alloys is also carried out in salt baths. When properly designed very uniform results are obtained, while at the same

time there is good protection of the material itself from oxidation. The size of the salt bath is in its favour for continuous work, since it is an excellent "heat reservoir" and less liable to fluctuating temperature, provided it is not overloaded. In modern plants the furnaces or salt baths are invariably controlled by thermostats and can be held within the required 10° range without difficulty. The precipitation treatment plant may be an oil bath similarly controlled, although forced-circulation furnaces are often used (Fig. 38).

The light aluminium alloys of the wrought type harden after cold working, but they should be annealed both before and after forming. If they are to be subsequently heat-treated after fabrication, of course, the second anneal can be omitted. Any local cold work on large sheets or sections, such as bending and forming, can quite often be successfully annealed by carefully going over the area affected with a blow-lamp until it has attained the proper temperature. Since no soaking in the ordinarily accepted sense is required, the heat can be taken away as soon as the part reaches temperature, and the risk of damaging the part is very small if the lamp is in skilful hands.

CHAPTER VIII

Drawing Up a Programme

In planning a heat treatment programme for any particular job, every point must, of course, be considered on its own merits, and the procedure mapped out with a view to keeping costs down to a reasonable level. At the same time, it is desirable to maintain the quality of the work at as high a standard as possible so that, broadly stated, the problem becomes one of balancing simplicity with efficiency. In dealing with large numbers of parts which have to be heat treated it will usually be found that time and handling costs are the most important, and various devices may be introduced to reduce some of these losses. Automatic controlling gear can go a long way towards eliminating the need for furnace attendants being on duty continuously. Mechanical handling of parts into and through the furnace is advantageous for continuous duty where the work can be adapted to this kind of treatment, and the quantities justify the special equipment, as, for example, in the mass heat treatment of high tensile bolts. In a job of this kind it is possible to obtain plant in which the rough bolts are fed in at one end, passed through the heating chamber and quenched mechanically, the work being carried on heat-resisting chain belts from the beginning to the end of the process. Naturally such a plant shows to its best advantage when it can be operated 24 hours a day continuously.

Furnace Capacity

Furnace capacity has also a bearing on the economics of heat treatment. A large furnace which can be maintained at a constant temperature fully loaded over long periods is making the best possible use of the heat, and from this point of view, can be said to be very efficient. If the temperature of the same furnace were to be changed frequently for different work and the load were also changed, the efficiency would be very low indeed, since much of the heat would inevitably be lost in the changing. In a furnace arranged for box carburising more or less continuously, the temperature will always be maintained

at about 900° C. It would be extremely wasteful in the majority of cases to use a small furnace and allow it to cool down with each batch. The economics of this case demand that the furnace be as large as possible and continuously maintained at the proper temperature. Mechanical handling plant will then make it possible to charge and discharge the hot furnace easily and the minimum heat is lost between charges. In cases where it is necessary to "furnace-cool" the work, either after carburising or annealing, the furnace loss is unavoidable, and consequently must be accepted as part of the cost of the treatment. It will thus be obvious that great care should be taken, when drawing up a working programme, that wasteful operations are eliminated as far as possible.

The work to be treated also calls for some comment. Most large hardening shops deal, as a matter of routine, with the heat treatment of such parts as drop forgings in order to put them in a suitable condition for the first machining operations. This involves operations such as normalising and, in some cases, hardening and tempering. It is apparent that furnaces suitable for this type of work need not have an elaborate atmosphere control, whereas furnaces for heat treating the finished parts may require it. If atmosphere control is not available, it will then be necessary to make sure that a sufficient machining or grinding allowance is left on the heat-treated part so that it will clean up properly. Another point arises in this connection, namely, distortion. Most steel parts distort to a greater or less extent in hardening or tempering. For example, a large-diameter ring of thin section will most probably go oval on quenching, while long rods, particularly if of varying section, will often twist in the most unexpected manner. Even thick and relatively rigid parts will show some signs of warping after quenching, and, of course, due allowance must be made for this in the final machining. Such distortion, arising from the impossibility of obtaining a perfectly uniform quench, may give rise to cracking if the design is weak. Sudden changes in section, drilled holes and sharp re-entrant angles are the principal causes of such quenching cracks. Accordingly, the programme should be drawn up with a view to avoiding these weaknesses.

Typical Programmes

In the light of the foregoing general remarks, it will be seen that heat treatment on a mass-production basis, in which

the physical properties of the parts must be held within narrow limits, demands a good deal of co-operation between the design office and the treatment shop. In fact the draughtsman must know something of the limitations of the heat-treatment plant available, while the heat treater must also learn to appreciate the engineer's ideas and help to give them practical shape. The heat treater and the engineer by working together can also improve the technique of a job by designing jigs and tools for special work. The writer has seen some most ingenious quenching jigs designed by an engineer in collaboration with a heat treater which successfully quenched small rings without distortion, and doubtless similar co-operation would yield equally satisfactory results in other cases.

Perhaps the most satisfactory method of showing how the pitfalls are avoided would be to take a typical hardening-shop job and go through it in detail. Accordingly, we shall consider the purely imaginary gear shown in Fig. 39. An examination of the sketch will reveal that this wheel requires to be casehardened all over the teeth, in the bore and on the sides of the flanges. The groove and outside diameters of the flanges are to be soft, as are also the sides of the wheel below the teeth. Assuming that the steel is a casehardening nickel-chrome type to the following analysis:

Carbon	Nickel	Chromium
0.15%	1.25%	0.75%

the procedure would perhaps be on the following lines.

Simplifying the Procedure

The rough forging, as received from the makers, would probably be in the "as forged" condition, that is, it would be of very variable hardness and machinability. Assuming that a large number of these forgings are to be machined, some effort should therefore be made to bring them all as nearly as possible to the same condition, thus avoiding tooling difficulties. Accordingly, the first step would be to normalise the forgings as received. This is accomplished by placing them into a furnace and heating them for about one hour, more or less, depending on their mass, and then drawing them and allowing them to cool freely in air. With a steel of this type it should be quite unnecessary to cool in the furnace, but with higher alloy steels, furnace cooling might become essential to obtain the required softness. The forgings are now ready for machining. These operations would include cutting the teeth to within a few

thousandths of an inch in size, and a similar allowance would be made on the other case-hardened surfaces. The bore would be machined out 0.005 in. small to allow for cleaning up after carburising. Whether the remainder of the wheel and the flanges are machined nearly to size at this point or not will depend entirely on the hardening procedure to be adopted. Two courses are open: (a) to carburise the whole wheel and machine away the parts not required, and (b) to machine the wheel very nearly to size and copper-plate the parts which are to be left soft. Which course to adopt depends on the equipment available, the number of parts and the relative speeds of the two operations. For a mass-production job (a) is faster and better adapted to modern machining methods, and we shall assume that this is the method to be adopted. The first machining will therefore leave sufficient allowance on the flange diameters to allow of the case being subsequently turned off. This allowance need not be more than $\frac{3}{16}$ in. and is sometimes less, but a generous allowance does no harm and ensures that the case is removed completely. The depth of case required has now to be fixed, and this will probably be of the order of 0.045 in. This gives the hardener some idea of the time required for carburising. The partly machined wheels are now ready for carburising. They should be carefully packed in boxes containing the carburising compound, the lids sealed on, and charged to the furnace to be raised to the carburising temperature, say 900° C. On completing the necessary time at this temperature the boxes will then be withdrawn and allowed to cool off. The wheels are now ready for the second machining operations. At this stage the flanges would be turned down to size plus a small cleaning-up allowance, and the deep groove and the sides of the wheel below the teeth turned, thus removing the case from the parts not required. The wheel is now ready for final hardening. It would be heated to 860° C., soaked for perhaps half an hour, and oil quenched. This refines the core and renders it tough. The case, however, though hard, will still be brittle, so that a second heat will be necessary. To refine and harden the case, the wheel would be reheated to 770° C. and again oil quenched. In order to toughen the hard case the wheel would be finally tempered at 200° C. In this condition, the soft core of the wheel will have a tensile strength of about 55 tons per sq. in., with about 15% elongation. After this treatment all that remains to be done is to clean up the

various faces, usually by grinding to the exact dimensions required.

An examination of the above procedure will show how a modern mass-production shop must have a systematic programme for each job and also why very exact heating and quenching instructions must be issued. Interchangeability and uniformity of material must be obtained at all costs if the treatment of large numbers of parts is to be conducted economically. For the first, dimensional accuracy must be obtained; for the second, temperature accuracy is necessary.

Tool Hardening

Tool hardening as a rule is a somewhat different proposition, since in most shops the quantity of such work is small, and as a result it has become something of a specialist's job. Small hand tools and odd lathe tools do not call for any comment here as they are not usually found in sufficient numbers to justify a special programme being drawn up unless these parts are encountered fairly frequently. In most shops the regular heat treatment suitable for the steel will be found adequate, and they can then be treated economically on a small batch basis as soon as a furnace at a suitable temperature becomes available. Large and expensive tools such as broaches often justify a careful study before manufacture, since even in the untreated condition they represent a fairly heavy capital expenditure in machining. This would be completely lost if failure occurred during the heat treatment, and it is to prevent such a disaster that a suitable programme should be drawn up even though this job may not be of frequent occurrence.

A Practical Example

Perhaps the best way to illustrate this statement will be to analyse a programme for a fairly long solid broach of circular section suitable for internal splining. In this case the tool would be essentially a bar of tool steel with sharp cutting edges machined on it. These edges would constitute sharp angles which would be potential weak spots on quenching and at the same time could be readily overheated in a badly regulated furnace. Consequently the first requisite for the successful treatment of such work would be a furnace capable of being held at the exact hardening temperature so as to preclude the possibility of overheating the delicate edges. The quenching equipment must also be designed to minimise warping of the

bar. For this purpose a steel which will fully harden in oil is to be preferred to a water hardening type and, moreover, the bar should preferably be quenched in a vertical position. This requires a deep oil tank. If a deep tank is unobtainable, a good support such as a basket must be used and the bar laid horizontally on it. Special precautions to guard against distortion in this case are desirable and quenching should be as rapid and complete as possible.

The steel itself must also be considered. In this particular case, hardness associated with a certain amount of toughness is to be desired in view of the type of work which is to be performed. A water-quenched high-carbon steel would give the necessary hardness but the fine edges with sharp re-entrant angles would almost certainly give trouble, and so a steel which develops a high cutting hardness with a milder quench would be preferable. The introduction of an alloy in a high-carbon analysis is the obvious solution and the one most frequently adopted. Accordingly it is usual to find that high-carbon chrome and similar steels are often specified for work of this nature. A suitable analysis would be as follows:

No.		Carbon		Manganese		Chromium
1	...	1.0%	...	0.4%	...	1.0%
2	...	0.9%	...	1.2%	...	0.5%

Steel No. 1 in the table above would be a good oil hardening type, while No. 2, in virtue of its much higher manganese content, represents a non-deforming tool steel and is also oil hardening. The advantage of No. 2 lies in the very slight dimensional change (due to the manganese) experienced on hardening. This type of steel will naturally reduce the chances of distortion considerably and is thus valuable for work of the kind under consideration. The other tool steel, of course, will distort badly unless special precautions are taken.

It is assumed that the steel, before machining, will be received as rolled from the steelmaker. In this condition it is likely to give rise to machining difficulties because of uneven hardness, and so the first step should be to anneal or normalise the bars. The usual procedure is to heat to 850° C., soaking for about one hour per inch of section and either air or furnace cooling. After this treatment the bars should be quite uniform and easily machinable. Occasionally even softer bars are required for machining than can be easily obtained by annealing and a "spheroidising" treatment is undertaken. This

consists of heating the previously normalised bars at a temperature just under A_{c1} for a long period. Such a treatment will soften tool bars to about 180 Brinell and give them a good "free machining" quality. Normalising, however, will be found in most cases to provide an excellent starting material.

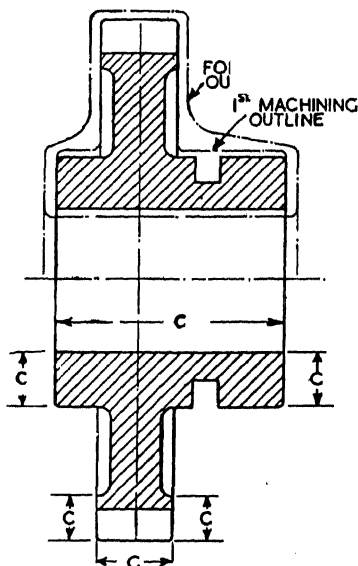


Fig. 39.—Section of gear-wheel to be heat-treated so that the points marked C will be casehardened. The section also shows the outline of the original drop-forging

The bars are now in condition for machining roughly to size. They should be of ample diameter to allow of at least $\frac{3}{8}$ in. being turned off the largest diameter and still leave the parts oversize by about $\frac{3}{16}$ in. Bores should, of course, be left the same amount small. After this rough turning operation, machining stresses will have cold worked the surface layers of the steel. To avoid warping as a result of this, it is desirable to anneal or normalise once more, but the need for this will depend greatly on the amount of stock removed in the first machining operation. A second machining operation should now take the rough broach to within, say, $\frac{3}{16}$ in. of finished size, this operation being finished off by grinding to about 0.020 in. oversize. Final hardening is accomplished by carefully packing the broach in charcoal in a box which is sealed from the air and slowly heating to the hardening temperature, usually 800° to 850° C. Plenty of time must be given for the

work to reach the temperature selected and the furnace should be capable of maintaining this very steadily. The broach is now quenched in oil, preferably by immersing vertically to avoid distortion, but if this is impossible, due to limitations of equipment, it may be laid horizontally on a basket and quenched rapidly. Instead of heating in boxes, of course, the cyanide bath may be used, the principal object being to avoid scaling with consequent decarburisation. Final grinding to exact sizes after tempering at 200° C. in oil only remains to complete the treatment. After hardening and before tempering it is usually possible to set cold any slight warp, especially if the straightening operation is performed immediately after hardening. It is a curious property of hardened steel that it remains slightly ductile for an hour or so after quenching, thus permitting a certain amount of straightening. If this is not done immediately, however, the steel rapidly stiffens up and may fracture on attempting to set it. This is probably an "ageing" phenomenon connected with precipitation hardening.

The foregoing explanations of typical commercial programmes will be enough to show how carefully a production job has to be planned in advance. It will be appreciated also that often a certain amount of experimental investigation will have to be undertaken before a final decision can be made, since many unexpected difficulties are likely to appear. Such difficulties may involve a change in design to overcome them, but more often a little ingenuity on the part of the heat-treater can evolve a successful method of attack. Full co-operation between the design office and the heat treatment shop is imperative to secure the best results, and it will be needless to labour the fact here that heat-treating artifices are but poor substitutes for sound design.

Hardening Shop Layout

The layout and equipment of a modern hardening shop is worth some consideration. The furnaces, of course, should be placed in the best positions in relation to the type of work handled. A "straight line" flow of work through the shop is desirable and can be very largely realised in large shops handling quantities of repetition jobs. Modern plants have mechanical charging and conveying gear installed as a matter of course, since man power for this type of work is merely wasteful. Most heat treatment plants have a variety of

furnaces, usually somewhat specialised in their duties, and it is the business of the shop superintendent to see that each is kept working as continuously as possible, preferably without wide variations in temperature. This involves considerable planning and as much work as possible coming in for treatment well ahead of schedule in order to allow for delays and rearrangements. However, if a machine shop is being fed with heat-treated products, great care will have to be taken that such rearrangement of programme does not interfere with the shop output, so that statements regarding the economics of shop procedure should not be interpreted too rigidly in practice. Quite conceivably occasions can and do arise when it is undoubtedly in the best interests of all to put through a small quantity of work in a large furnace or to cool off a hot furnace for a special job knowing full well that it will have to be reheated immediately afterwards.

The essentials of a modern shop so far as equipment is concerned would be on the following lines. There might be two large furnaces capable of reaching 1000° C., one of which could be employed for ordinary casehardening on a more or less continuous basis. The other could handle large annealing, normalising, hardening and other jobs, and would have suitable quenching tanks for oil and water nearby. The carburising furnace would be mechanically charged, since this type of work is usually put through in batches. A small self-contained plant for hardening high-speed and other steels might be desirable also if this type of tool hardening is to be undertaken, the actual size of the plant being governed by the amount of such work expected. In this connection the question of controlled atmospheres for the various furnaces should be considered. Here, again, the exact nature of the work will be the deciding factor. As an adjunct to the heat treatment shop a copper-plating plant will be required for "stopping off" parts for casehardening, while a pickling bath and sand-blast will be necessary for cleaning and descaling rough forgings and semi-finished products. A certain amount of inspection of the parts both before and after treatment will also be undertaken, such as hardness testing, checking the progress of carburising, and similar duties, and provision should be made to have this carried out as near the furnaces as possible. Overhead cranes are also desirable for handling heavy loads into and out of the shop.

Of course the nature of the work largely decides the form

taken by the hardening shop and the amount of special equipment required. For example, the hardening and tempering of such products as bolts and similar small articles on a mass production basis would be better performed, from the cost point of view, by a moving-hearth type of furnace. In this case the process resolves itself into simply feeding the untreated bolts into one end of the plant and withdrawing them, finished, at the other. The time of treatment is set once and for all by regulating the speed of the hearth, and the bolts, as they drop off the hearth into a quenching tank, are removed by a conveyor. Not all jobs, however, lend themselves to such automatic treatment, and many cases will arise in practice which require individual treatment. It is in dealing with these cases that the writer hopes he has helped to enlighten his readers.

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